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Abstract

The objective of this paper is to analyze the relationship of the carbon Kuznets curve. We discuss two potential flaws in past carbon Kuznets curve studies: one, the potential misspecification of energy consumption as a control variable; and, two, the use of vector error correction models as an empirical specification. Given these potential flaws we estimate a dynamic ordinary least squares model of monthly carbon dioxide emissions, personal income, and energy production in the U.S. from 1981 to 2003. Our results suggest that economic growth drives emissions intensities, not absolute emissions as is often implied in past studies. © 2013 Society for Policy Modeling. Published by Elsevier Inc. All rights reserved.

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1. Introduction

The objective of this paper is to integrate the approaches of the environmental Kuznets curve (EKC), decomposition analysis, and energy-growth based on three relatively independent streams...
of literature into one cohesive discussion on the nexus among energy, the environment, and the economy. Developing a discussion will aid in our understanding of energy resources as one of the major factors affecting both the economy and the environment. With current discussions surrounding global climate change, greenhouse gas emissions (GHGs), and economic development, the results within this study imply that economic development (including energy infrastructure development) can be beneficial to the environment (and arguably is necessary for environmental quality improvements). The environmental benefits of economic development as suggested by the EKC hypothesis are not to discredit those that advocate for sustainable growth, but rather to further the energy-pollution-income debate so that the public is aware of policies alternative to the limits-to-growth argument. More importantly, energy policy could play a significant role in stimulating economic development while at the same time ameliorating harmful pollution emissions.

This study offers a unique contribution to the literature in four ways. The first contribution involves an empirical example in which we synthesize the three separate literatures outlined below. The second contribution is noting the potential flaw in many past studies that have empirically estimated the effects of energy use and economic growth on carbon dioxide emissions. Namely, carbon dioxide emissions in many past studies are estimated based upon energy consumption within a particular jurisdiction. Several studies then proceed to specify a covariate of energy consumption on the right-hand side (RHS) of the model, which may lead to spurious empirical results due to simultaneity bias. The third contribution is to point out the potential flaw in specifying a dynamic econometric model, such as a vector autoregressive (VAR) model or vector error correction model (VECM), which are popular in many recent studies. Subject to these potential flaws we estimate a dynamic ordinary least squares (DOLS) model among monthly time series of U.S. personal income, CO₂ emissions (based upon U.S. monthly energy consumption), and energy production from 1981 to 2003. Our fourth contribution constitutes the use of high frequency, monthly data from 1981 to 2003. Many past studies use annual data that miss potential inter-annual variation in the time series variables. Further, the higher frequency data provide better asymptotic qualities for dynamic regression analysis. Using this uniquely high frequency of data we find a long-run relationship between the variables that suggests the inverted-U shaped relationship between CO₂ emissions and personal income as espoused by the EKC. However, based upon our estimated data for CO₂ emissions, our results may suggest that this relationship is instead between CO₂ emissions intensities and income.

2. Background

2.1. The environmental Kuznets curve

The EKC hypothesis came to prominence in the 1990s after the early works of Grossman and Krueger (1991, 1995), Shafik and Bandyopadhyay (1992), and Selden and Song (1994). The first EKC papers were advanced by trade/developmental economists in the context of international trade agreements. Since these three initial papers the EKC literature has developed into a rich examination of both the empirical and theoretical aspects of the relationship between the environment and the economy. According to Carson (2010), “[the] lasting contribution of the EKC literature has been to shift the conventional wisdom of rank-and-file economists and many policy makers toward a belief that economic growth is good for the environment.” Yet, despite this robust literature there has been until recently a paucity of EKC
studies examining the role of energy in the relationship between economic growth and the environment.3

According to the EKC hypothesis, economic growth itself may be a vehicle that reduces pollution emissions. This hypothesis describes the time path that pollution follows through a country’s economic growth cycle. Specifically, this hypothesis states that environmental degradation follows an inverted U-shaped relationship as a country’s economy grows over time.

Since the conception of the hypothesis, researchers have examined a wide variety of pollutants seeking evidence of the EKC. Separate studies have experimented with different econometric approaches, including: different orders of polynomials, fixed and random effects, semi-parametric and non-parametric techniques, splines, and different covariates specifications (Levinson, 2008). Past studies have also examined different jurisdictions and time periods. Full reviews of the EKC literature are available in such works as Dinda (2004), Levinson (2002), Stern (2004), and Lieb (2004), among others.

The main arguments against the EKC hypothesis are: (1) the assumption of the causal role of economic growth and (2) the inadequacy of the reduced-form econometric models to adequately describe the generation of the pollution of interest (Carson, 2010).

2.2. Decomposition methods

The decomposition approach usually constitutes some type of identity or tautological formulation. This identity then can be used to construct an index that examines the differing trends within the determining factors. In general, decomposition methods are used for descriptive analyses, but more complex specifications of the model can be used with statistical procedures. For example, the IPAT model, which was inspired by the limits-to-growth or sustainability literature (Hirsch, 1977; Mishan, 1967; Schumacher, 1973), uses a multiplicative specification to explain the pressures driving pollution emissions (Commoner, 1972). More specifically, the IPAT model decomposes environmental impacts (I) into population growth (P), economic affluence (A), and technology (T). Another such decomposition method includes the Kaya Identity named after the Japanese energy economist Yoichi Kaya. The Intergovernmental Panel on Climate Change (IPCC) uses both the IPAT model and Kaya Identity to estimate carbon dioxide emissions. The IPAT model not only highlights the contribution of population growth to environmental pressures but draws attention to the fact that numerous factors interact to form a compounding effect on the environment. The factors interact multiplicatively as $I = P \times A \times T$; or the confluence of population growth, economic affluence, and technology have a detrimental impact on the environment – this equation is simply an accounting identity. One of the more common expressions of the IPAT equation is listed as

$$I = \frac{\text{Population}}{\text{Population}} \times \frac{\text{Income}}{\text{Income}} \times \frac{\text{Pollutant}}{\text{Pollutant}},$$

where $I$ denotes pollution (Chertow, 2001). The second term on the right-hand side of (1) is the affluence term and the third represents technology. The IPAT equation is an extension of the Ehrlich and Holden (1971) equation of $I = P \times F$, where $F$ is defined as a function that measures per capita impact.

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3 Energy’s role in the growth-pollution relationship is implicit in most EKC studies examining greenhouse gas emissions; however, energy’s direct role is less often explicitly analyzed.
Although the IPAT model is useful in determining trends among the factors to pollution, the model is generally limited to the evaluation of a single variable measure such as carbon dioxide or sulfur dioxide emissions. Further, studies have found that different types of air pollutants react differently to changes in population, affluence, and technology (Cole & Neumayer, 2004).

Despite these limitations, several studies have used IPAT or other decomposition methods to analyze the determining factors of carbon emissions (Greening, Davis, & Schipper, 1998; Hamilton & Turton, 2002; Liaskas, Mavrotas, Mandaraka, & Diakoulaki, 2000; Lise, 2006; Roca & Alcantara, 2001; Schipper, Ting, Khrushch, & Golove, 1997; Stern, 2002). Roca and Alcantara (2001) in particular use a decomposition method to analyze the role of primary energy consumption in CO2 emissions. The authors then use the decomposition to further dissect the EKC hypothesis into a weak and strong form. The weak form implies that there is a de-linking between environmental pressure and economic growth as the intensity of emissions decreases when income increases (Roca & Alcantara, 2001). The authors argue that the relevant issue is not the evolution of emission intensities but rather the trend in absolute emission levels. They posit that economic growth can only mitigate emissions if the intensity of environmental pressure lessened due to the increase in GDP, and the rate of decrease of emission intensity is higher than the rate of GDP growth. They define the latter argument as the “strong” form of the EKC hypothesis.

2.3. Energy-growth literature

Following the oil crises in the 1970s, a body of literature emerged that examines the relationship between energy consumption and economic growth.⁴ This energy-growth literature explores the causal link between energy consumption and economic activity, and after three decades of empirical research there is still no general consensus on the causal link between energy consumption and real GDP. A full survey of the literature is available in Payne (2010). According to the author, the lack of consensus is due to the heterogeneity in climate conditions, differing energy consumption patterns, differing stages of economic development, alternative econometric methodological approaches, and omitted variable bias. Payne (2010) suggests that future research should attempt to bridge the energy consumption-growth literature with the research on the relationship between growth and emissions such as the environmental Kuznets curve.

2.4. Integration of methods

Several recent studies have begun to integrate the EKC and energy-growth approaches either explicitly or implicitly (Aldy, 2005; Ang, 2007, 2008; Pao & Tsai, 2011; Pao, Yu, & Yang, 2011; Soytas & Sari, 2009; Soytas, Sari, & Ewing, 2007). These studies rely on a mixture of 1) causality tests including variants of Granger causality and bounds testing, and 2) dynamic econometrics models including dynamic ordinary least squares (DOLS), cointegration analysis, vector error-correction modeling, etc. Similar to the separate EKC and energy-growth literatures, these synthesized papers find mixed results for the dynamic relationship between pollution emissions, economic growth, and energy.

There are two potential flaws with several of these past studies. One of the potential problems with several of these studies (Ang, 2008; Apergis & Payne, 2009; Halicioglu, 2009; Pao et al.,

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⁴ Throughout the rest of this paper we will use the terms energy consumption and demand interchangeably, although this is technically not correct as energy consumption is observable (ex post concept) whereas energy demand is a latent variable (ex ante concept). Therefore, we primarily will refer to energy consumption in our discussion.
is that they use CO₂ emissions data which are estimated from energy use or consumption. In other words, these past studies do not examine actual measures of carbon dioxide emissions – these emissions rather are calculated from energy statistics (Itkonen, 2012). Several papers use the World Bank’s World Development Indicators data base which contains CO₂ emissions data from the Carbon Dioxide Information Analysis Center (CDIAC) within the U.S. Department of Energy. The CDIAC estimates emissions by multiplying coal, petroleum, and natural gas consumption by their respective thermal conversion factors.

Several past studies proceed by specifying an explanatory variable for energy consumption on the right hand side (RHS) of the empirical model. The independent variable of energy consumption is then simultaneously determined with the dependent variable. This small insight calls into question the validity of past results as such specifications may lead to simultaneity bias; i.e., when one or more of the explanatory variables is jointly determined with the dependent variable.

A second flaw involves the specification of dynamic models to estimate the relationship. VECM models appear to be one of the more popular specifications in recent studies. The potential problem with these models is that generally all the variables must be integrated of the same order to yield stationary residuals. For example, all the variables may be integrated of order one which implies that the series is characterized by a unit root. The problem with applying an EKC analysis to VECMs is that any higher order polynomial such as a square transformation of the income series (consistent with the EKC hypothesis) may asymptotically enlarge its order of integration, and conventional Dickey–Fuller tests often lack the power to detect this (Granger & Hallman, 1991). Other potential pitfalls with the VECM specification is mis-specifying the deterministic components of the cointegrated model (Ahking, 2002), and in our experience with this specification there is a question of the stability of the estimates of the VAR and VECM models. Further, a recent study by Itkonen (2012) reveals that a VECM is misspecified because the assumption of normally distributed i.i.d. error terms, which is required for the VECM, cannot be satisfied and the estimates are not reliable. This perhaps explains the instable estimates with our attempts of a VECM (and VAR) regression analysis.

To overcome these potential flaws we specify a cointegrating model that has been far less prevalent in the literature – dynamic ordinary least squares (Stock & Watson, 1993). DOLS allows for cointegrating vectors of higher order integrated systems. We discuss DOLS further in Section 3.2.

3. U.S. carbon dioxide emissions

Given the different results among the EKC, IPAT, and energy-growth literatures, we synthesize these three approaches into an integrated examination of the relationship among carbon dioxide

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5 Wang (nd) tries to account for this by specifying the square root of second term of income instead of income squared as in typical EKC studies. Although creative this specification does not allow one to test the inverted-U shaped relationship of the EKC hypothesis.

6 A VECM model is sensitive to the number of cointegrating relationships in the specification. If the process is stable, then the cointegrating equations contain eigenvalues that are strictly less than one. This stability condition was very questionable in our attempts of VECM specification of the energy, growth, and emissions relationship (not provided). See Enders (2010) for further details about the stability conditions for a VAR or VECM. These conditions are rarely discussed in past studies.

7 An exception is Aldy (2005) who uses DOLS to estimate a panel of U.S. state-level CO₂ emissions using a similar dataset.
emissions, energy supply, and economic growth in the U.S. The first approach links the IPAT model to the EKC hypothesis. The second approach links the EKC and energy-growth models. We use CO₂ emissions, personal income, population, and energy supply as an empirical example to frame the two approaches. Finally, we use our empirical results from the two approaches to more fully examine the relationship between emissions, growth, and energy.

3.1. IPAT analysis

The IPAT decomposition examines the trends in factors driving carbon dioxide emissions in the U.S. In order to derive the index we rewrite (1) as

\[
\text{CO}_2 = \frac{\text{Population}}{\text{Population}} \cdot \frac{\text{Income}}{\text{Income}} \cdot \frac{\text{CO}_2}{\text{CO}_2}.
\]

Carbon dioxide emissions are measured in thousands of metric tons on a monthly basis (Carbon Dioxide Information Analysis Center, 2011). Population is based on monthly estimates of the U.S. population (Bureau of Economic Analysis, 2011). Current-dollar or real personal income is measured in billions USD on an monthly basis (Bureau of Economic Analysis, 2011). We use personal income as a proxy for national affluence as GDP is not measured on a monthly basis. Energy supply is generally defined as indigenous production, plus imports, less exports, and plus (or minus) current stocks (International Energy Agency, 2012). As a proxy for energy supply we use U.S. primary energy production which is measured in billion Btu (Energy Information Administration, 2011). Primary energy production consists of coal, natural gas, crude oil, biomass, etc.

Taking the derivative of (2) with respect to time and then dividing the entire equation by CO₂ yields the following

\[
\frac{\dot{C}}{C} = \frac{\dot{P}}{P} + \frac{\dot{(Q/P)}}{(Q/P)} + \frac{(\dot{C}/Q)}{(C/Q)},
\]

Eq. (3) indicates that the growth rate of CO₂ emissions is equal to the sum of the growth rates of population, per-capita income, and CO₂ emission intensity of output. Additionally, the emission intensity term can be further decomposed as

\[
\frac{(\dot{C}/Q)}{(C/Q)} = \frac{(\dot{C}/E)}{(C/E)} + \frac{(\dot{E}/Q)}{(E/Q)}.
\]

where \(E\) denotes primary energy production. Eq. (4) indicates that the growth rate of CO₂ pollution intensity is the sum of the growth rates of CO₂ intensity of energy and energy intensity, respectively.

We plot the index of (3) by setting the base-year (1981) equal to ten. Fig. 1 plots out the monthly growth rate of CO₂ based upon the growth rates of each of the factors in (3) from 1981 to 2003.

Fig. 1 indicates that energy-related CO₂ emissions have been on the rise since 1981, although not monotonic with a clear seasonal pattern. This trend comes from the fact that emissions are estimated based upon energy consumption, and energy consumption in the electric power sector (one of the largest contributors to national CO₂ emissions) is characterized by seasonality. During
Fig. 1. IPAT decomposition.

this same period the U.S. population and per-capita income both indicate clear increasing trends. Consistent with Ehrlich and Holden (1971), this decomposition seems to indicate that population growth and affluence are placing pressure on energy-related CO₂ emissions; i.e., we observe an increasing trend in both factors and an increasing trend in CO₂ emissions. The growth rate of emission intensity indicates a slight increase initially and then a leveling throughout the entire period. This factor captures either improvements in technologies such as more efficient fossil-fuel combustion over time, or a change in the fossil fuel mix which in turn changes the carbon intensity (such as switching to less-carbon intensive forms of coal or switching from coal to natural gas).

Considering all these factors, population growth and affluence seem to overwhelm technology improvements as we observed an increasing trend in carbon dioxide emissions over this period as consistent with Fig. 1. Thus, it appears that economic growth has detrimental effects on the environment as it leads to additional carbon dioxide pressures.

In accordance with Roca and Alcantara (2001), economic growth would be environmentally “friendly” in the weak sense (or what they define as the weak form of the EKC) if we observe a decrease in emission intensities when income increases. This is partially revealed by the last factor (\(C/Q\)) in Fig. 1; i.e., emission intensities are at least leveling throughout the latter period of observation. Economic growth is friendly in the strong sense (or strong form of the EKC) if the intensity of environmental pressure lessened due to an increase in income and the rate of decrease is higher than the rate of income growth (Roca & Alcantara, 2001). The authors’ definition of “strong” implies a decrease in emissions through time

\[ \dot{C} < 0. \]
Based upon (3) this implies,

\[
\frac{\dot{C}}{C} = \frac{\dot{P}}{P} + \frac{\dot{Q}/P}{Q/P} \frac{\dot{C}/Q}{C/Q} < 0.
\]

Rearranging terms yields

\[
-(\frac{\dot{C}/Q}{C/Q}) > \frac{\dot{P}}{P} + \frac{\dot{Q}/P}{Q/P}.
\]

In order to satisfy the definition of the strong form of the EKC, the rate of decrease in emission intensity \((C/Q)\) must be higher than the rate of increase in both population and per-capita income growth collectively. Based upon Fig. 1, it seems that economic growth is environmentally friendly (with CO₂ emissions) in the weak sense but not in the strong sense as we observe national CO₂ emissions increasing not decreasing.

To see how energy factors into our IPAT model we decompose emission intensity into the emission-intensity of energy (i.e., the ratio of emissions to energy use) and energy intensity itself as defined in (4). Using this decomposition we construct an index of pollution intensity based upon these factors for the same period in Fig. 2.

Fig. 2 indicates that emission intensities \((C/Q)\) exhibit a slight increasing trend followed by a leveling of growth throughout the rest of the period. This increasing trend appears to be driven by the increase in CO₂ per unit of energy produced \((C/E)\). This same figure indicates a decreasing trend of energy intensities \((E/Q)\). The decrease in energy intensity potentially captures technological improvements, changes in the fossil fuel mix, or a reduction in fossil fuel consumption due to environmental regulations. Since the rate of change of emission intensities is composed of energy intensity and CO₂ per unit of energy supply it appears that the increase in CO₂ per unit of energy produced is outweighing the decrease in energy intensity, thereby driving up emission intensities.
Although these two opposing forces may be near in off-setting one another as we observe a leveling of emission intensities towards the end of the period.

These findings seem to contradict a EKC hypothesis for energy-related CO₂ emissions in the U.S. over this period (at least according to the “strong sense” as defined by Roca and Alcantara (2001)). This would also contradict an argument for the benefits of economic development (or simply an increase in economic output) in ameliorating these emissions in the U.S. If this is true then it may suggest that energy conservation policies may be more effective at mitigating emissions. However, we need to also examine how energy conservation measures may affect economic growth in the U.S. Since the IPAT model is merely a descriptive analysis it is difficult to determine the interactions among emissions, energy consumption, and economic growth. Therefore, we develop an econometric approach to estimate the interactions among these variables to offer additional insights into these relationships.

3.2. **CKC analysis**

If two or more time-series variables are characterized by a unit root (or the variables are integrated of order one, \(I(1)\)), a simple regression between the variables will often yield significant \(t\) statistics (indicating a significant relationship) even though there may be no sense in which the variables are related – this is referred to as a spurious regression. This problem could potentially be overcome by considering cointegration between the two variables. Cointegration is the notion that a linear combination of two series, each of which is integrated of order one or higher, forms a stationary relationship. A stationary, linear combination between two time series suggests that the two have a long-run relationship. One can include an estimate of this long-run relationship on the RHS of an estimable model to capture short run and long-run dynamics between the two variables – this is referred to as an error correction model or a cointegrating model.

We begin our empirical analysis by examining the stochastic properties of the time series. These tests will help up determine whether the time series variables are trend-stationary series or integrated processes. Fig. 3 contains an index of the time series variables. The results for the tests are reported in Table 1. We first report the Kwiatkowski, Phillips, Schmidt, and Shin (1992) test for trend stationary series and report the test statistic at four lags. The null hypothesis for the Kwiatkowski et al. (1992) test is that the series is trend stationary, whereas the null hypothesis for the Augmented Dickey–Fuller Test (ADF) is that the series is characterized by a unit root (Elliott, Rothenberg, & Stock, 1996). The Kwiatkowski et al. (1992) test results in column three show that we can reject the null hypothesis of trend stationarity at the 5% level for income.

<table>
<thead>
<tr>
<th>Variables</th>
<th>KPSS test stat at lag 4</th>
<th>ADF test with a trend</th>
<th>ADF test without a trend</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The natural logarithm of</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1  CO₂</td>
<td>0.0515</td>
<td>−1.319 (14)</td>
<td>−1.407 (14)</td>
</tr>
<tr>
<td>2  Income</td>
<td>0.644*</td>
<td>−1.760 (11)</td>
<td>−2.295 (8)**</td>
</tr>
<tr>
<td>3  Energy production</td>
<td>0.106</td>
<td>−3.205 (12)**</td>
<td>−2.163 (12)**</td>
</tr>
<tr>
<td>4  Population</td>
<td>0.101†</td>
<td>−2.490 (13)</td>
<td>−1.129 (13)</td>
</tr>
</tbody>
</table>

\( (k) \) denotes the optimal lag length chosen by a modified Akaike’s information criterion.

* Denotes the rejection of the null hypothesis at the 10% significance level.

** Denotes the rejection of the null hypothesis at the 5% significance level.
and population. Columns four and five report the augmented Dickey–Fuller (ADF) test with and without a trend, respectively. The number in parentheses indicates the optimal lag length according to a modified Akaike’s information criterion. The results show that all time series with the exception of energy production are $I(1)$ processes. Although, the ADF test on national income rejects the null hypothesis of $I(1)$ when a trend is not included.

Next we proceed to use the Engle–Granger two stage procedure to determine if there is a long-run (stationary) relationship among the time series variables (available upon request). This procedure is well-developed in the literature, and further details can be found in Engle and Granger (1987). The procedure consists of regressing CO₂ emissions on energy production, population, and the quadratic specification of income, both with and without a time trend. The residuals of this regression are derived and then tested using ADF critical values to determine if the series contains a unit root. The critical values from the second stage of this procedure indicate that we reject the null hypothesis that the residuals contain a unit root; and the test statistics are highly statistically significant (at the one percent level) implying that the residuals are stationary and a long-run relationship exists among these variables.

The estimated parameters of the Engle–Granger first stage regression are consistent, but the estimates are inefficient relative to a simple extension of the regression model – namely, dynamic ordinary least squares. Moreover, the standard errors and $t$ statistics are non-standard, so hypothesis testing is no longer valid. To fix the efficiency problem and to correct the standard errors and $t$ statistics we use heteroskedastic and autocorrelation consistent (HAC) standard errors (Newey–West standard errors). DOLS is a very simple estimation procedure consisting of leads and lags of the differences of the integrated variables in the regression model. The differencing procedure corrects for stochastic trends within the time series variables, and the lead and lags control for serial
correlation. This procedure captures potential short-run dynamics in addition to the long-run, cointegrating relationship.

To account for the seasonal trend within the CO₂ emissions we include variables for heating degree days (HDD) and cooling degree days (CDD). HDDs are deviations below the mean daily temperature of 65 ⁰F, and CDD are deviations above the same temperature.

The results for two different specifications of the DOLS procedure are listed in Table 2. To save space, we list only the results for the cointegrating variables (i.e., the long-run relationship among the variables). We specified the short-run dynamics with twelve leads and lags as we have monthly data. In the first specification we applied the leads and lags to the difference of income, income squared, and population as we failed to reject the null hypothesis of each containing a unit root in Table 1. With the first specification all the variables are statistically significant except for population. Energy production is positively related to CO₂ emissions as expected. HDD and CDD are negative which is not consistent with expectations as cooler months would be expected to increase the demand for heat, which in turn should increase CO₂ emissions as more fossil fuels are combusted to generate electricity to meet that demand (and vice versa for CDD). However, according to Blasing, Broniak, and Marland (2004), peak winter months may reflect more natural gas consumption which decreases CO₂ emissions because it is more environmentally friendly than the other fossil fuels. Further, the evolution of environmental regulations in the U.S. may have encouraged less carbon-intensive forms of fossil fuel combustion over this period – this may certainly apply with the passage of the second amendment to the Clean Air Act in 1990. The income terms are consistent with a long-run EKC hypothesis in the U.S. over this period.

With the second specification in Table 2 we excluded the energy production variable as it may be highly related to energy consumption. In other words, it may be difficult to distinguish between the variation in production and consumption as the two have a tendency to move in tandem through time. In this second specification all the variables are statistically significant except for the income terms. The coefficients on HDD and CDD do not change much from the previous specification.

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8 Natural gas emits 56.1 t CO₂ per TJ, whereas oil emits 73.3 t CO₂ and coal emits 94.6 t CO₂ (Bhattacharyya, 2011).

### Table 2
Dynamic ordinary least squares results.

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>Coef.</th>
<th>Newey–West S.E.s</th>
<th>t</th>
<th>P &gt;</th>
<th>95% Conf. interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Specification with energy variable:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>0.52266</td>
<td>0.0960</td>
<td>5.49</td>
<td>0.0000</td>
<td>0.3374–0.7159</td>
</tr>
<tr>
<td>Pop</td>
<td>0.7813</td>
<td>0.6058</td>
<td>1.29</td>
<td>0.1990</td>
<td>−0.4135–1.9760</td>
</tr>
<tr>
<td>CDD</td>
<td>−0.0561</td>
<td>0.0080</td>
<td>−7.03</td>
<td>0.0000</td>
<td>−0.0719–−0.0404</td>
</tr>
<tr>
<td>HDD</td>
<td>−0.0554</td>
<td>0.0045</td>
<td>−12.42</td>
<td>0.0000</td>
<td>−0.0641–−0.0466</td>
</tr>
<tr>
<td>Income</td>
<td>1.1246</td>
<td>0.4135</td>
<td>2.72</td>
<td>0.0070</td>
<td>0.3092–1.9400</td>
</tr>
<tr>
<td>Income Sq.</td>
<td>−0.2517</td>
<td>0.1315</td>
<td>−1.91</td>
<td>0.057</td>
<td>−0.5110–0.0076</td>
</tr>
<tr>
<td>(2) Specification without energy variable:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pop</td>
<td>1.1084</td>
<td>0.4842</td>
<td>2.29</td>
<td>0.0230</td>
<td>0.1526–2.0642</td>
</tr>
<tr>
<td>CDD</td>
<td>−0.0503</td>
<td>0.0088</td>
<td>−5.70</td>
<td>0.0000</td>
<td>−0.0678–−0.0329</td>
</tr>
<tr>
<td>HDD</td>
<td>−0.0514</td>
<td>0.0047</td>
<td>−11.06</td>
<td>0.0000</td>
<td>−0.0606–−0.0423</td>
</tr>
<tr>
<td>Income</td>
<td>0.7525</td>
<td>0.5186</td>
<td>1.45</td>
<td>0.1490</td>
<td>−0.2711–1.7762</td>
</tr>
<tr>
<td>Income Sq.</td>
<td>−0.2163</td>
<td>0.1403</td>
<td>−1.54</td>
<td>0.1250</td>
<td>−0.4933–0.0607</td>
</tr>
</tbody>
</table>
The income terms are still consistent with the inverted U-shaped relationship, however they are no longer significant. A possible explanation for this lack of significance is that energy production and personal income are highly correlated, so excluding the energy production variable results in omitted variable bias that biases the income coefficient downward.

Itkonen (2012) points out two potential flaws with past studies of the relationship among energy, economic growth, and CO2 emissions. The first flaw implies that if our estimates of energy production are highly related to energy consumption then the effect of income on carbon dioxide emissions can only be interpreted as an effect on “carbon intensity” of the underlying fuel mix used to calculate the CO2 emissions. If this is the case then the statistical significance of the income terms (consistent with the EKC hypothesis) may be somehow related to the reduction in CO2 intensity that we observe in Fig. 1.\(^9\) In this case, income is not driving down CO2 emissions but rather the carbon intensity of the underlying fuel mix used in the U.S. In other words, the underlying fuel mix is changing to a less carbon-intensive mixture—such as switching from coal fired to gas-fired electricity. This is consistent with our findings in the IPAT decomposition in which we claimed that economic growth appears to be environmentally friendly in the “weak” sense as defined by Roca and Alcantara (2001).

The other potential flaw pointed out by Itkonen (2012) is that there is a misspecification bias arising from the dependence between energy production and income. To test for this we ran an auxiliary regression between the two time series (available upon request)—our regression results did not suggest a significant relationship between these two variables. Nevertheless, if there is a relationship between energy production and income then the specifications in Table 2 do not account for this, and according to Itkonen (2012) this may imply that the turning point of emissions will occur later than estimated.

4. Policy implications and conclusion

In this paper we discussed and then synthesized the three separate literatures of the EKC, decomposition methods, and energy-growth. Our synthesis involved an examination of the relationship among CO2 emissions, energy production, and national income in the U.S. over the period 1981–2003 using a dynamic ordinary least squares model. The empirical results suggest the existence of a long-run relationship between the variables that is consistent with the environmental Kuznets curve hypothesis—these results are similar to Ang (2007). To complement the findings we used the IPAT model to decompose CO2 emissions into the factors of population growth, economic growth, and technological growth. The IPAT analysis seems consistent with “weak” form of the EKC but seems to contradict the EKC hypothesis in the “strong” form as defined by Roca and Alcantara (2001). Due to how CO2 emissions are estimated, our regression results may capture the relationship between CO2 emission intensities and income (Itkonen, 2012), which is consistent with the IPAT decomposition.

These findings may suggest to policy makers that economic growth is relieving some pressure on the environment in terms of carbon intensities in the U.S. but not absolute emissions. This is consistent with what we observe in Fig. 1 as we observe an initial increasing trend in CO2 emission intensities followed by a leveling (or probable decreasing) of intensities over this period.

\(^9\) It is worth noting here, that Itkonen’s definition of carbon intensity differs from the definition according to the IPAT model. Carbon intensity, according to Itkonen (2012), refers to the emissions ratio of carbon emissions to energy consumption. The definition in the IPAT model refers to the carbon intensity of output which is the ratio of carbon emissions to output.
This would suggest that perhaps an economic stimulus policy may be an effective approach in ameliorating but perhaps not completely mitigating CO₂ emissions. Therefore, our findings seem to suggest that conservation policies (e.g., energy conservation policies) may need to be coupled with economic stimulus policies to mitigate emissions as a whole. In other words, our results suggest that income in the form of GDP is not sufficient in and of itself to relieve the pressure of carbon dioxide emissions.

We outlined several problems, within the carbon Kuznets curve literature, that have practical implications for climate change mitigation policy. First and foremost, the CKC is based upon a reduced-form specification so it is difficult to infer causality or make policy prescriptions concerning the relationship among economic growth, energy demand, and environmental degradation. Moreover, we outlined several problems within the literature that merit further attention. One of the principle problems is in regards to how carbon dioxide emissions are estimated – because these emissions are estimated from energy use one needs to be careful in the interpretation of econometric models which use energy consumption as an explanatory variable. The interpretation of coefficients which are consistent with the EKC hypothesis needs to interpreted with caution as to whether the results can be interpreted as an actual decrease in emissions or a decrease in intensity. Further, statistical evidence of a decrease in emissions may be sensitive to the type of times series model selected as we pointed out the potential problem with the stability conditions of such models which use a quadratic specification.

In the future, a global reduction in CO₂ emissions is going to be based upon multilateral agreements between nations. The connection between economic growth, energy, and emissions will have a significant impact on the political economy of negotiating such agreements. Therefore, as future studies seek to determine the connection between the economy, energy, and emissions it is important to be cognizant of the potential issues pointed out in this study. That is, future studies need to exercise caution in how carbon dioxide emissions are measured and how to interpret decreases in emissions. Any such findings of decreases are sensitive to the chosen explanatory variables and time series model selected.

References


Wang, Y.-C. (nd). *Short- and long-run run environmental Kuznets curve: Case studies of sulfur emissions in OECD countries*. Online; accessed April 2011.