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The Economic and Energetic Determinants of Carbon Emissions and the Implications for Development and Environmental Policy

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Kuznets, Kaya, and Shapley: The economic and energetic determinants of carbon emissions and the implications for development and environmental policy

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Abstract

With global climate change becoming an increasingly pressing concern, the relationship between economic growth and environmental outcomes is as important as ever to understand, particularly in designing policies for low- and middle-income countries that incorporate both environmental and development objectives. The Environmental Kuznets Curve (EKC) shows the relationship between income and environmental outcomes. In this paper we examine the existence and shape of the EKC for 132 countries for the period 2000-2010. We add to the EKC literature by using the technique of Shapley Decomposition to assess Kaya identity factors for these 132 countries, grouped into income quartiles. The Kaya Identity relates emissions to income, energy intensity, and emissions intensity. Shapley Decomposition (SD) allows us to understand the importance of each of these factors. By applying the SD technique to the Kaya Identity for countries grouped by income level, we can assess the importance of income on emissions for countries at various stages of development, and we confirm the presence of a global EKC. For lower income countries, rising income is the most important determinant of emissions; but at higher income levels economic growth is offset by improvements in energy efficiency and decarbonization, thus explaining the inverted-U-shaped EKC.

Keywords

Energy; Environment; Development; Economic Growth; Decomposition Analysis; Emissions

1. Introduction

The search for the proof of an Environmental Kuznets Curve (EKC) is much like the search for proof of the Loch Ness monster. Some economists claim to have seen it, others claim it exists but cannot be seen, and yet others claim its non-existence.

The EKC hypothesizes a relationship between income and environmental quality. At lower income levels, economic output is low, energy use is correspondingly low, and emissions of carbon dioxide or other air pollutants are therefore low as well. As economic output rises, energy use and concomitant pollution rise, reaching the peak of the upside-down U-shaped curve. Eventually, income levels rise enough that an economy transitions from energy-intensive and pollution-heavy industries to a more service-oriented and lower-polluting economic structure. In addition, with higher income levels and higher standards of living, individuals develop a demand for amenities such as clean air and water, goods that seem to be luxury goods at lower levels of economic activity. Economies at higher levels of income also have the financial resources to invest in cleaner technologies and to enforce environmental regulations.

If this theory holds true, then the relationship between income and air pollution, or income and carbon emissions or some other indicator of environmental quality, should take the form of an inverted-U; there should be a quadratic relationship in which the turning point occurs at middle income levels.

Empirical evidence of the EKC is mixed. Methodological approaches are varied. Some economists have analyzed the correlation longitudinally, by comparing income and environmental outcomes of a country or set of countries over time, as the income of that country or set of countries has grown (Riti et al., 2017; Kwakwa & Adu, 2016). Others have studied cross-sectional data (Grossman & Krueger, 1991, 1995); Kerr & Mellon, 2012). And yet others have examined panels of data – wherein the relationship between income and environmental quality is captured over time for a cross-section of countries or areas (Al-Mulali & Ozturk, 2016; Bilgili, Kocak, & Bulut, 2016; Farhani, Mrizak, Chaibi, & Rault, 2014; Ozokcu & Ozdemir, 2017). Using all of these methods, there has not been a consistent and conclusive relationship between income and environmental quality (henceforth referred to as EQ), though the preponderance of studies does suggest the presence of an EKC with an inverted-U shape. Excellent and vast literature reviews have recently been published by Tiba and Omri (2017) and Al-Mulali and Ozturk (2016), showcasing the variety in the methods, geographical concentrations, and time periods of EKC studies.

Why is this important? What can we learn from this relationship and how could it inform policy? The existence and form of the EKC are important for development policy, in particular as it relates to environmental policies. It is of particular concern for the welfare and development potential of the least-developed countries as well as for middle-income countries. If it is true that the EKC exists, it does not necessarily imply that a pro-growth strategy will without exception lead to lower emissions. What it does imply, however, is that it is possible to pursue a growth strategy without growing emissions, or even to pursue growth while emissions decline (or, in other words, while EQ improves).

We would like to stress here that the presence of the EKC shows a relationship between income and environmental quality, and not necessarily causality; in other words, if the EKC is in fact an inverted U, implying that emissions eventually decrease with rising income, this is *not* the same as implying that the solution to climate change is economic growth. What it *does* imply is that declining emissions are *possible* even with economic growth. From this we can conclude two things: First, that low- and middle-income countries should not be prevented from pursuing economic growth because of a fear of rising emissions; and second, that environmental policy is of the utmost importance in bringing about the declining emissions trend that we often see in higher-income countries – that policies to increase economic growth must be coupled with policies to increase energy efficiency and to shift to lower-carbon sources of energy if we are to bring about declining emissions.

Carbon emissions have become an increasingly important global concern, and the stabilization and reduction of carbon emissions have become goals for most countries. The Paris Climate Agreement, coordinated by the United Nations, signed by 197 parties and ratified by 174 (as of January 2018), sets a target of limiting global temperature change to no more than 2 degrees Celsius above pre-industrial levels. Countries at all levels of development have signed on to this agreement and are making efforts to control carbon emissions. Development policy must therefore be aligned not only with the aims of increasing standards of living including increased income, education, and healthcare, but also with the improvement of environmental outcomes.

While the EKC explores the relationship between income and emissions, the Kaya identity includes energy intensity, carbon intensity, and population as additional factors in describing environmental outcomes. For ethical reasons, I prefer not to leave the Kaya identity in its popular form, where the implication is that controlling population is a means toward reducing emissions. Instead, I divide both sides of the equation by population, so that we have per capita emissions instead of total emissions on the left-hand side of the equation. I will refer to this re-arranged form as the "Pollin Identity."[1]

$$\text{Emissions/Population} = (\text{GDP/Population})*(\text{Energy Use/GDP})*(\text{Emissions/Energy Use}) \qquad [1]$$

The EKC essentially relates the left-hand side of the Pollin identity to the first term of the right-hand side (y). But the Pollin identity includes two other factors: energy intensity (e) and carbon intensity (c). Energy intensity and carbon intensity can positively or negatively affect per capita emissions. As an economy becomes more energy efficient, and as it transitions to lower carbon energy sources, *e* and *c* can have a downward pull on emissions, and can even become great enough (independently or in combination) to offset the emissions-increasing effect of income growth. This would describe the negative slope of the EKC as income rises from middle levels to high levels.

In order for the Pollin identity to be relevant for policy, we want to know not only whether each factor has a positive or negative impact, but also the size of the impact in comparison to other factors that determine per capita emissions, and in particular how a change in these factors impacts a change in emissions over time. In order to study the direction, size, and dynamics of the RHS elements, I use the Shapley Decomposition.

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[1] The Pollin Identity is named after Robert Pollin, an economist at the University of Massachusetts who has written extensively on the topic of "Green Growth" and has used the Kaya identity in this re-arranged form to show how per capita emissions can be quite similar in countries that have very different levels of per capita income.

Shapley Decomposition is used in game theory to assess the marginal contribution of one player to the outcome for all players in a cooperative game (Shapley, 1953). I use Shapley Decomposition here to measure the marginal contribution of changes in per capita income, energy efficiency, and carbon intensity, to the total change in per capita emissions. One contribution made in this paper is to estimate the individual country Shapley values for 132 countries at various levels of development, and then an innovation is to group these countries into income quartiles and estimate the Shapley values of the quartiles. A second innovation in this paper is then to use the Shapley values of income effects for each quartile to estimate the equation for a global EKC.

I use data from the World Bank's "World Development Indicators" for all countries, for the years 2000 and 2010. Having eliminated countries with missing data, I end up with a dataset that includes 132 countries at all income levels. I estimate the Shapley values for each of the Pollin factors for each country. I then group these countries into income quartiles. Finally, using the decomposition results for these quartiles, I estimate a quadratic polynomial with the Shapley value for the income effect as the independent variable and per capita emissions as the dependent variable. I find the existence of an inverted-U-shaped EKC. Having isolated the marginal contribution of income growth to emissions growth by using the Shapley Decomposition, we see that the EKC does in fact hold globally for the period 2000-2010.

2. Background

In this section I present some of the background on the three areas of research interwoven in this paper: The Environmental Kuznets Curve (EKC); the Kaya Identity; and the Shapley Decomposition technique. Each of these elements has its own body of research and each has distinct relevance for economic policies that consider both development and environmental goals.

2.1 Environmental Kuznets Curve

The Kuznets Curve is based on the work of Simon Kuznets, who in the mid-twentieth century posited a concave function relating income inequality to a country's stage of economic growth. Kuznets hypothesized that at lower income levels, the disparity between rich and poor is not large; then, as a country undergoes further economic development and national income rises, the income gap between rich and poor grows; eventually, however, the gap narrows again at higher levels of national income. Environmental economists applied this same inverted-U-shaped trajectory to the relationship between economic growth and environmental quality, leading to a body of research on the Environmental Kuznets Curve (EKC).

In a 2004 review, Dinda surveyed the literature and recent theoretical and methodological developments relating to the EKC (Dinda, 2004). Dinda summarizes what still remains the case in this area of study, which is that evidence on the existence of the EKC is mixed, and that the EKC hypothesis seems to be valid for certain air pollutants but not for all. Writing in the same era, Raymond (2004) separates the opponents and proponents of the EKC into various camps: (1) The Neo-Malthusians with a "limits to growth" view; (2) Those who see economic growth as the key to environmental and human prosperity; and (3) "Ecological Modernization," which is somewhere in between. We might nowadays call the third position "Green Growth." Raymond notes that particular types of air and water pollutants, especially those with more immediate and locally contained effects, have been most consistent with the EKC pattern. EKC relationships with carbon emissions have been identified by many researchers, but with different turning points and varying outcomes, supporting the rejection of the EKC hypothesis (Raymond, 2004).

Writing more recently, various economists have shown that the same controversy still exists regarding the EKC (Rafaj et al. 2014; Kaika & Zervas, 2013). Kaika and Zervas review the state of the EKC literature and find mixed evidence of the inverted-U hypothesis. They enumerate various possible causes of an EKC include, which I present in the table below:

Table 1: Factors affecting emissions and determining EKC

Potential driver of emissions changes (factors affecting shape of EKC)	**Hypothesized effect**
Equity of income distribution	More equitable income distribution is associated with stronger pollution abatement; if economic growth is equitable, emissions can decline, otherwise they will rise
International trade and pollution havens	Trade shifts production of energy-intensive or pollution-intensive goods to middle-income countries, away from higher-income countries, thus pollution grows for middle-income and falls for higher-income countries
Structural change and technical progress	In early stages of development, expanding economic activity is associated with greater extractive and polluting activities; then at middle levels of development an economy is primarily industrial; at higher levels it shifts toward more services and less associated pollution.
Energy intensity and mix	Countries that can afford to adopt greater levels of technological innovation will use more energy-efficient technology and shift to lower-carbon energy
Institutional framework and governance	Countries with higher levels of economic activity tend to have stronger political institutions and better governance, allowing for the regulation and enforcement of activities that affect the environment
Consumer Preferences	As countries reach higher levels of economic activity, consumers develop preferences for amenities such as clean air and water and may have a willingness to pay for these goods (such as through taxes that can be used for pollution abatement)

Source: Adapted from Kaika & Zervas (2013)

Tiba and Omri (2017) provide an excellent and extensive review of the EKC literature covering the period 1978-2014. The authors survey more than one hundred studies, including single-country and multi-country studies. These studies use various techniques to assess the nexus of economic growth and energy consumption, including Vector Error Correction Models (VECMs), Variance Decomposition, Auto-regressive Distributed Lag (ARDL) models, various methods to assess Granger causality, and other techniques. Tiba and Omri show that these studies have mixed results when it comes to the direction of causality between GDP and energy consumption, and that in some cases the causality is bi-directional. In assessing studies of the EKC in particular (see their Table 4), Tiba and Omri show that the vast majority of studies support the EKC hypothesis.

In another recent and significant survey of the EKC literature, Al-Mulali and Ozturk (2016) show the wide variety of methods, geographical areas, and time periods used in EKC studies. Here, too, they find that there is overwhelming support for the EKC hypothesis. Al-Mulali and Ozturk then add to the literature by including energy prices as an explanatory variable, finding that an increase in energy prices leads to reduced energy consumption and therefore reduced emissions.

Another somewhat recent development in the EKC literature is an examination of other possible shapes of the EKC, including N-shaped (Allard et al., 2018; Ozokcu and Ozdemir, 2017; Lipford & Yandle, 2010), inverted-N-shaped (Ozokcu and Ozdemir, 2017; Yang et al., 2015; Kaika and Zervas, 2013), or M-shaped EKC (Yang et al., 2015). The N-shaped EKC would imply that emissions could start rising again in the highest income countries; M-shaped implies that there is a double hump rather than single hump as in the inverted-U. The inverted-N I would assert is a misnomer, since inverting the letter N actually results again in the letter N. What is really meant in these studies is a mirror-N, wherein emissions begin by falling as income goes from very low to low, then emissions rise in the second stage of income growth, then fall again. So this essentially tacks on a declining trend at very low income levels and then moves into the inverted-U pattern; whereas with an N-shaped curve, we start with the inverted-U and then tack on rising emissions at high levels of income.

Lipford and Yandle (2010) find an N-shaped EKC for most G-8 countries (except Russia), and they describe the importance of public choice in determining the shape of the EKC. These authors claim that more affluent countries establish environmental regulations that result in a decrease in emissions, but that after a certain point the regulations become too costly or the preference for regulation shifts, resulting in a decrease in regulation or pollution controls and rising emissions at the tail.

I will note here that from a policy standpoint, what matters in all cases, whether the EKC is an inverted-U, or N-shaped, or the mirror-N, is that policy is established and enforced to encourage energy conservation and efficiency as well as replacement of high-carbon by low-carbon energy as economic growth is pursued.

Another more recent development in the EKC literature is a renewed focus on trade. As noted by Carson (2010), the EKC literature started not with environmental economists but with trade economists, as Grossman and Krueger (1991) evaluated the effects of the North American Free Trade Agreement (NAFTA) on emissions levels in the U.S. and Mexico. Grossman and Krueger noted three possible categories of impacts that would explain the EKC: (1) Growth, or an increase in the scale of production, which would increase emissions; (2) Composition effects, or the structure of the economy, namely that a shift toward more services could decrease emissions while an increase in energy-intensive manufacturing would increase emissions; and (3) Technology, which could have positive or negative effects on emissions. Carson notes that the composition effect “has ambiguous effects in any one country but could not result in a reduction in pollution everywhere (Carson, 2010, p. 7).” This captures in one sentence what the effect of trade is on emissions. As a country shifts toward a service-oriented economy, it imports more manufactured goods. Its emissions fall as a result. But emissions will rise elsewhere in the world, as another country (or countries) now produce those manufactured goods for export. Thus the composition effect could raise or lower emissions in any one country, but can not lower emissions globally. Globally lowering emissions could only happen through the technology effect (a shift to lower-polluting technology, better pollution control devices, lower-carbon technology, and so on). The role of trade has been recently incorporated into various papers on the EKC or the relationship between growth and environment more generally (Allard et al., 2018; Al-Mulali & Ozturk, 2016; Ben Jebli, Ben Youssef, & Ozturk, 2016; Bilgili, Kocak, & Bulut, 2016; Dobes, Jotzo, & Stern, 2014).

2.2 Kaya Identity / Pollin Identity

What has now become fairly well-known as the Kaya identity was originally presented in a paper by electrical engineering professor Yoichi Kaya in a working group of the U.N.’s Intergovernmental Panel on Climate Change in 1989. The Kaya identity relates to a more general version of an impact identity used by the IPCC and referred to as IPAT (the acronym of the identity below):

$$\text{Impact} = \text{Population} \times \text{Affluence} \times \text{Technology} \quad [\text{IPAT}] \tag{2}$$

$$\text{CO2 emissions} = \text{Population} \times (\text{GDP/Population}) \times (\text{Energy/GDP}) \times (\text{CO2/Energy}) \quad [\text{Kaya}] \tag{3}$$

In both cases, the identities relate right-hand-side drivers of emissions including population (itself generally a driver of economic output), level of economic development (“affluence” or GDP per capita), and either technology per se or energy intensity and emissions intensity, both of which are driven by the state of technology. These RHS factors jointly contribute to the environmental “impact” or level of CO2 emissions. The IPCC notes that “the four terms on the right-hand side of the equation should be considered neither as fundamental driving forces in themselves, nor as generally independent from each other” (Nakicenovic & Swart, 2000). While the RHS terms interact, the Kaya identity is useful in decomposing the sources of emissions growth (or reductions) and enabling us to see which factors are more important than others in driving a change in emissions.

The Kaya identity, in essence, relates energy consumption to carbon emissions. Greater population and economic output generally lead to an increase in energy consumption and therefore an increase in carbon emissions. However, these increases can be offset by an increase in energy efficiency (which is a decrease in energy consumption per unit of GDP) and/or a decrease in the carbon content of the fuel mix. Some authors have taken this a step further to separate GDP into sub-components such as energy use by sector, where the sectors might include transport, households, and industry (see, for example, Agnolucci, et al., 2009) or alternatively have decomposed the term for energy use into various types of energy use (e.g., fossil and non-fossil).

The two right-most terms in the Kaya identity, energy intensity and carbon intensity, reflect the state of technology in energy provision and consumption - and in the EKC literature mentioned above, technology is an important determinant of emissions trends. Technological developments that permit greater energy conservation and efficiency, or those that control pollution or lower the carbon content of energy sources, lead to a reduction in carbon emissions. Thus technology is generally seen as the most important factor in the declining emissions trends in higher-income countries (Dobes, Jotzo, & Stern, 2014; De Cian et al., 2013; Kerr & Mellon, 2012). Carbon intensity can improve by switching from higher-carbon fossil fuels (coal) to lower-carbon fossil fuels (oil and gas), or by switching to more nuclear power or renewable energies such as wind, solar, or geothermal energy (Deutch, 2011).

Deutch notes that while the Kaya shows that emissions reductions would occur through either carbon intensity or energy intensity improvements, there are various ways to accomplish these. He claims that energy efficiency is the most cost-effective choice, and that this can be achieved either through regulatory mandate or by raising energy prices so that there is a market incentive to use less energy (Deutch, 2011, p. 38). “Decoupling” is the term used in the environmental literature to describe the severing of the connection between economic growth and energy use, or between “economic goods” and “environmental bads” (Kerr and Mellon, 2012, p. 266). This is what we would expect to see in the upper portion of the EKC: rising GDP with falling emissions.

It is important to keep in mind that the Kaya identity does not establish causality. It is an accounting identity, not a regression with parameters, and thus a change in any one of the RHS factors will of course change the LHS term. An important next step, then, will be to use a method of analysis to determine how important a movement in any of the RHS factors is in changing the LHS term.

Having identified carbon emissions (or other pollutants) as the product of its various components, we then use decomposition analysis to estimate the size and direction of the effects of each component on carbon emissions, which is useful and important for developing appropriate climate and development policies.

2.3 Decomposition Techniques

Below we will dive into greater details regarding the methodology of decomposition. Here I provide some brief background on decomposition analysis as it relates to the overarching goal of this paper, which is to link the EKC with the Kaya components and thus to isolate the effects of income on emissions while also recognizing the roles of energy consumption and the energy mix.

Some of the main forms of decomposition analysis that have been applied to energy and emissions include structural decomposition analysis (SDA); index decomposition analysis (IDA); log-mean divisia index (LMDI), which is a subset of IDA; regression-based inequality decomposition; and others. In an oft-cited paper on this topic, Hoekstra and van den Berg (2003) review and compare SDA and IDA. They note that these techniques have been used to analyze changes in energy demand, emissions, labor demand, and value-added. SDA uses information from input-output tables (a national accounting system) where IDA uses aggregate data at the sector level. The techniques were developed independently, and both are used to assess the level and direction of driving forces on indicator changes. SDA generally assesses absolute changes in variables, while IDA is used for absolute changes, intensity changes, and elasticities.

In a more recent paper, Su and Ang (2012) include an update to Hoekstra and van den Berg's comparison of SDA and IDA. One of the developments that occurred in the interim was the development of SDA methods that are "ideal" in decomposition, meaning that there are not unexplained residuals in addition to the contributions of the determining factors. Furthermore, previous ad hoc methods of decomposition were dependent on the sequence of factors involved, since generally one factor would be changed while others were held constant. The order in which each factor was held constant would influence the size of the effect of the factor. Ideal decomposition ensures both that there are no residuals (i.e. the decomposition is "exact") and that the decomposition passes the "factor-reversal test," meaning that the order in which factors are added and removed or held constant does not impact the size of their effect. Su and Ang further describe additive forms of decomposition, including LMDI (this is the method generally used by Ang in other publications), the S/S method (named for Shapley and for Sun), and the MRCI method. What is referred to in other research as the "Shapley Decomposition" is referred to as the S/S method by these authors, since Sun proposed the method in a 1998 paper while Albrecht et al. (2002) independently propose using the Shapley Decomposition for the same purpose.

Decompositions can be either additive or multiplicative in form. Su and Ang (2012) classify the Shapley Decomposition or S/S method as an additive approach within the Laspeyres family of decompositions. LMDI is, of course, in the Divisia-based approach. Su and Ang note that in the early 2000s both S/S and LMDI were equally used, but that over time researchers came to prefer LMDI as the dominant method at least partly due to its greater ease of use. Using the LMDI decomposition method, researchers such as Zhang and co-authors have been able to isolate the drivers of carbon emissions and have found that increased economic output was the dominant factor in increased carbon emissions in China, and that while energy intensity and economic structural changes can offset the rise due to scale effects, in the case of China in the years 1995-2005, changes in energy intensity and economic structure were not great enough to offset rising emissions due to output (Zhang et al. 2011). Similarly, O'Mahony (2013) evaluates the emissions drivers in Ireland using the LMDI approach for the period 1990-2010 and finds that the dominant effect is the affluence effect, and that the emissions effect was positive but fairly small and that the energy intensity effect was negative but not enough to outweigh the effects of the other factors. What O'Mahony refers to as the "emissions effect" is the carbon intensity of the energy system, which in the case of Ireland in the period studied actually increased due to a shift to higher-emitting types of coal within the fossil fuel sector.

While LMDI may be the increasingly preferred approach for decomposition, other researchers have continued to use the Shapley decomposition technique, or the technique referred to as "S/S" by Su and Ang (2012). The S/S technique is sometimes considered to be more complicated than LMDI (Ang, 2004) but has seen continued use and has led to conclusions similar to those found by researchers using LMDI.

Albrecht et al. (2002), in a much-cited paper within this literature, were early proponents of using the Shapley decomposition technique in combination with the Kaya identity. They study the data for Belgium, France, Germany, and the United Kingdom for the period 1960-1996. They find that the Shapley technique shows the positive relationships between population, output, and carbon emissions, and that energy intensity and decarbonization of the energy mix have negative effects on carbon emissions. Like authors using the LMDI approach, they find that the economic growth effect was strong and positive and not sufficiently offset by energy intensity or decarbonization to lower emissions. However, the results showed variation between the countries in the relative importance of each factor.

Albrecht et al. note that the Shapley Decomposition technique has been used since 1953 in a number of cost allocation models. They discuss the historical problem of factor order in decomposition techniques, and that "the Shapley decomposition iterates the cumulative approach for every possible order (permutation) of variables." With *n* variables there are therefore *n!* calculations, and by taking the average of the *n!* estimated contributions for each variable, the Shapley value "yields the true contribution of each variable" (Albrecht et al. 2002, p. 731). This results in three major advantages: the Shapley Decomposition is perfect (no residuals); symmetric (order of factors does not matter); and it allows for very complex decompositions that would otherwise be plagued by large residuals.

One additional recent article that employs Shapley Decomposition focuses on emissions at the household level (Han, Xu, X., & Han, L., 2015). The authors seek to identify the emissions factors that are most salient for households in China, and compare households in different income quantiles. Before using Shapley Decomposition, the authors use quantile regression to determine which factors are relevant to emissions at the household level (household embedded carbon emissions, or HECEs). Then, in a second step, they use Shapley Decomposition to determine how much each of these factors has an impact on households in each quantile (in this case, in each decile). Han, Xu, and Han find that household income has a positive effect on emissions. But income has different effects for different quantiles. They find that the rich emit more than the poor, but that the rate has a declining trend, in other words it is not a monotonic relationship. Income and car ownership are the two biggest contributors to HECEs among across all income groups, but the size of the effect differs by quantile, and other factors vary in both direction and importance as the authors analyze different quantiles. While Han, Xu, and Han do not estimate an EKC, their method has some similarities to the methods I will employ, and stems from a similar conception, namely that factors which have an impact on emissions will have different sized impacts at different levels of income. While Albrecht and co-authors (2002) use Shapley Decomposition to assess the relative importance of emissions factors at the country level (as I will do), Han and co-authors (2015) assess this relationship across household income deciles within one county, China. But in both studies, what the authors find is that income matters, and that part of how it matters is in what income can purchase. At the country level, increasing income can purchase cleaner technologies and better pollution controls and regulations; at the household level, increasing income purchases cars and homes and things that consume energy, but is also correlated with higher education and likelihood of being employed, which in turn have their own effects on emissions. Thus, in both types of studies, income has both direct and indirect effects on emissions, and the Shapley Decomposition technique allows us to assess the size and direction of all of the factors that have been identified (in the Kaya identity or through quantile regression) as leading to a change in carbon emissions.

The above papers suggest a few things: One, that the Shapley decomposition technique is sound and tractable when working with a small number of factors, such as the three factors in the Pollin identity; secondly, that income is likely to be the biggest factor in determining emissions but is certainly not the only factor; and thirdly, that the size and direction of emissions factors may vary across income levels, and that therefore there it is valuable and meaningful to sort countries or areas of study into income groups.

3. Data and Methods

I have just presented background on the three strands of research I wish to weave together here: The EKC; the Kaya Identity; and Shapley Decomposition. In this section, I will present additional methodological details, particularly on decomposition techniques surveyed above, and I will show how we can use the Shapley Decomposition technique to assess the factors of the Pollin identity. I use data on emissions, GDP, energy intensity and carbon intensity from the World Bank, for the years 2000 and 2010 for 132 countries. I perform Shapley Decompositions for each of the 132 countries (results can be found in Appendix B); I also group the countries in income quartiles and perform the Shapley Decomposition on the quartiles. Then, using the results for the effects of income on emissions, I construct an EKC.

3.1 Data

I use data from the World Bank's "World Development Indictors" on the following indicators (descriptions and sources are listed in Appendix A):

CO2 emissions (metric tons per capita), years 2000 and 2010

Energy use (kg of oil equivalent) per $1 GDP (constant 2011 PPP), years 2000 and 2010

CO2 intensity (mt per kg of oil equivalent energy use), years 2000 and 2010

GDP per capita, PPP (constant 2011 international $), years 2000 and 2010

I start by gathering data for all of these variables for all countries in the WDI dataset. However, not all countries have reported data for both 2000 and 2010 for all of these variables, and therefore I drop the countries from the dataset that have missing data. This results in a dataset of 132 countries at all income levels.

I name the variables as follows:

cpc: CO2 emissions per capita

y: per capita income

e: energy use per $1 of GDP

c: CO2 intensity

Then the Pollin identity is written as:

$$cpc = y*e*c \quad [4]$$

To decompose the Pollin identity using the Shapley decomposition I first need to calculate the change in variables, so I create new variables as follows:

$Deltacpc = cpc_{2010} – cpc_{2000}$

$Deltay = y_{2010} – y_{2000}$

$Deltae = e_{2010} – e_{2000}$

$Deltac = c_{2010} – c_{2000}$

I then group our countries into four groups by their level of 2010 per capita income. I end up with the following income quartiles, with 33 countries in each quartile:

Table 2: INCOME QUARTILES, INCOME RANGE AND AVERAGE GDP PER QUARTILE

	GDP PER CAPITA, 2010		**AVERAGE GDP**
N=33	(in 2011 constant PPP $)		Within quartile
	Minimum in quartile	Maximum in quartile	
1ST QUARTILE	$ 596.32	$ 5,595.30	**$ 2,861.66**
2ND QUARTILE	$ 5,638.21	$ 13,845.28	**$ 9,767.58**
3RD QUARTILE	$ 14,405.93	$ 29,652.94	**$ 20,433.60**
4TH QUARTILE	$ 29,913.06	$ 127,670.61	**$ 48,565.63**

In the highest income group, Singapore is a significant outlier in terms of income growth and energy and emissions declines. Between 2000 and 2010, Singapore's GDP nearly doubled (99% increase in GDP per capita) while their carbon intensity and carbon emissions per capita declined massively. According to the data, CO2 emissions per capita fell from 12.17 metric tons to 2.66, while CO2 intensity fell from 2.63 kilograms per kilogram of oil equivalent energy use to 0.53. These changes in carbon emissions and carbon intensity seem too large to be plausible and cannot be verified by other data, and therefore could be a mistake in reporting or recording the data. Because of the possibility of data errors, and since the results for an income quartile can be quite skewed by a significant outlier such as Singapore is in this period, I run the results both with and without Singapore.

3.2 Shapley Decomposition

Shapley values determine the marginal contribution of any one player to a multi-player game. In this case we have a 3-player game in which the players are income (y), energy intensity (e), and carbon intensity (c). In its general format, the Shapley value for any one player is given by the following formula:

$$\varphi_i[v] = \sum_{S\subseteq N-\{i\}} \frac{s!(n-s-1)!}{n}[v(S\cup\{i\}) - v(S)] \qquad [5]$$

This formula captures all of the permutations possible with n! players and calculates each player's marginal contribution. The right-most term within the brackets represents the value-added of any one player in a cooperative game. The factorial terms in the numerator that pre-multiply this value-added term represent the different orders or permutations in which the players can make their moves (the order in which each policy or component is evaluated), and the divisor accounts for the total number of possible permutations, therefore providing an average of all possible contributions that each player or factor can make.

With three factors, there are six possible combinations of orderings, thus to obtain the Shapley value for each player, we add up the marginal contributions over the possible six orderings and then for each player we add up the marginal contributions of that player and divide by six (Inchauste et al., 2014).[2]

The Shapley Decomposition for an identity with 3 right-hand-side factors that we use here is as follows:

$$\Delta cpc = \Delta c[\tfrac{1}{3}(y_{t=1}*e_{t=1} + y_{t=0}*e_{t=0}) + \tfrac{1}{6}(y_{t=1}*e_{t=0} + y_{t=0}*e_{t=1})\ ] + \Delta e[\tfrac{1}{3}(y_{t=1}*c_{t=1} + y_{t=0}*c_{t=0}) + \tfrac{1}{6}(y_{t=1}*c_{t=0} + y_{t=0}*c_{t=1})\ ] + \Delta y[\tfrac{1}{3}(c_{t=1}*e_{t=1} + c_{t=0}*e_{t=0}) + \tfrac{1}{6}(c_{t=1}*e_{t=0} + c_{t=0}*e_{t=1})\ ] \qquad [6]$$

There are three terms on the right-hand side, each representing the contribution of one Pollin factor to the change in carbon emissions. The first term (starting with Δc) represents the contribution of carbon intensity, the middle term is the contribution of energy intensity, and the final term is the contribution of income.

We can then calculate three new Shapley variables from our data,

$$\mathit{Cbar} = \mathit{deltac}*(((y_{2010}*e_{2010}+y_{2000}*e_{2000})/3)+(e_{2000}*y_{2010}+e_{2010}*y_{2000})/6)/\mathit{deltacpc} \qquad [7]$$

$$\mathit{Ebar} = \mathit{deltac}*(((y_{2010}*c_{2010}+y_{2000}*c_{2000})/3)+(c_{2000}*y_{2010}+c_{2010}*y_{2000})/6)/\mathit{deltacpc} \qquad [8]$$

$$\mathit{Ybar} = \mathit{deltac}*(((c_{2010}*e_{2010}+c_{2000}*e_{2000})/3)+(e_{2000}*c_{2010}+e_{2010}*c_{2000})/6)/\mathit{deltacpc} \qquad [9]$$

From the Shapley variables – cbar, ebar, and ybar – we can then calculate the percentage points that each of c, e, and y contribute to the percentage change in per capita emissions (cpc).

$$\mathrm{Pcntc} = \mathit{cbar}*(\mathit{deltacpc}/\mathit{cpc}) \qquad [10]$$

$$\mathrm{Pcnte} = \mathit{ebar}*(\mathit{deltacpc}/\mathit{cpc}) \qquad [11]$$

$$\mathrm{Pcnty} = \mathit{ybar}*(\mathit{deltacpc}/\mathit{cpc}) \qquad [12]$$

And then

$$\mathrm{Pcntc} + \mathrm{pcnte} + \mathrm{pcnty} = \mathit{deltacpc}/\mathit{cpc} \qquad [13]$$

Or, equivalently:

$$[\mathit{cbar}*(\mathit{deltacpc}/\mathit{cpc})] + [\mathit{ebar}*(\mathit{deltacpc}/\mathit{cpc})] + [\mathit{ybar}*(\mathit{deltacpc}/\mathit{cpc})] = \mathit{deltacpc}/\mathit{cpc} \qquad [14]$$

---

[2] Note: For an excellent exposition of the logic and math underlying the Shapley Decomposition, I recommend the World Bank publication, "Understanding Changes in Poverty," (Inchauste et al., 2014).

I perform these calculations for each of our 132 countries, and then group the countries into quartiles by income level, as shown above. The average results are presented and discussed below, and the individual results are located in Appendix B.

4. Results and Discussion

This section presents the results for the Shapley Decomposition conducted for 132 countries, grouped into four income groups, for the period 2000-2010. The first set of results, shown in Table 2, does not include Singapore (which, as noted above, is an outlier in this time period), and thus only includes 131 countries. Table 3 shows the results for the highest income group when Singapore is included. The detailed results by country are located in Appendix B.

Table 3: RESULTS BY INCOME QUARTILE (NOT INCLUDING SINGAPORE IN HIGHEST QUARTILE)

Country groupings	***2010 GDP per capita, PPP (constant 2011 international $)***	***Number of countries in group***	***% change in cpc***	***% change in cpc attributable to…***		
				y	***e***	***C***
1ST QUARTILE	**$ 2,861.66**	**33**	**15%**	**21%**	**-13%**	**6%**
2ND QUARTILE	**$ 9,767.58**	**33**	**15%**	**31%**	**-17%**	**1%**
3RD QUARTILE	**$ 20,433.60**	**33**	**11%**	**35%**	**-24%**	**0%**
4TH QUARTILE W/O SINGAPORE	**$ 47,831.57**	**32**	**-6%**	**8%**	**-6%**	**-8%**

If I include Singapore in the results, the highest income group has very different results, since over the period studied (2000-2010), Singapore's income rose significantly while its emissions and energy use declined dramatically. The results for the highest income group including Singapore are here:

Table 4: RESULTS FOR HIGHEST INCOME QUARTILE, INCLUDING SINGAPORE

	2010 GDP per capita, PPP (constant 2011 international $)	*Number of countries in group*	*% change in cpc*	*% change in cpc attributable to…*		
				y	***e***	***C***
4TH QUARTILE INCL. SINGAPORE	**$ 48,565.63**	**33**	**-17%**	**11%**	**-8%**	**-20%**

Since the above results show averages for each income group, the Pollin factors may not sum exactly to the percentage change in emissions. However, for each individual country, they do – this is what shows that the Shapley decomposition is perfect and ideal.

First, we note the percentage change in per capita emissions over the years 2000 to 2010. As we might expect, the lowest income groups saw the biggest increase in emissions. Both the bottom and second quartiles saw a 15 percent increase in emissions over the period. The third income quartile saw emissions increase as well, though slightly lower than the bottom half of the distribution, with per capita emissions increasing 11 percent over the period. Finally, the highest income quartile saw a decrease in emissions of six percent if we do not include Singapore, or a 17 percent decline if we include Singapore.

For all income groups, income had the greatest positive effect on emissions. For the bottom three quartiles, energy efficiency had the greatest negative effect on emissions. Carbon intensity had a positive effect for the two bottom quartiles, zero effect for the third, and a negative effect for the highest income group.

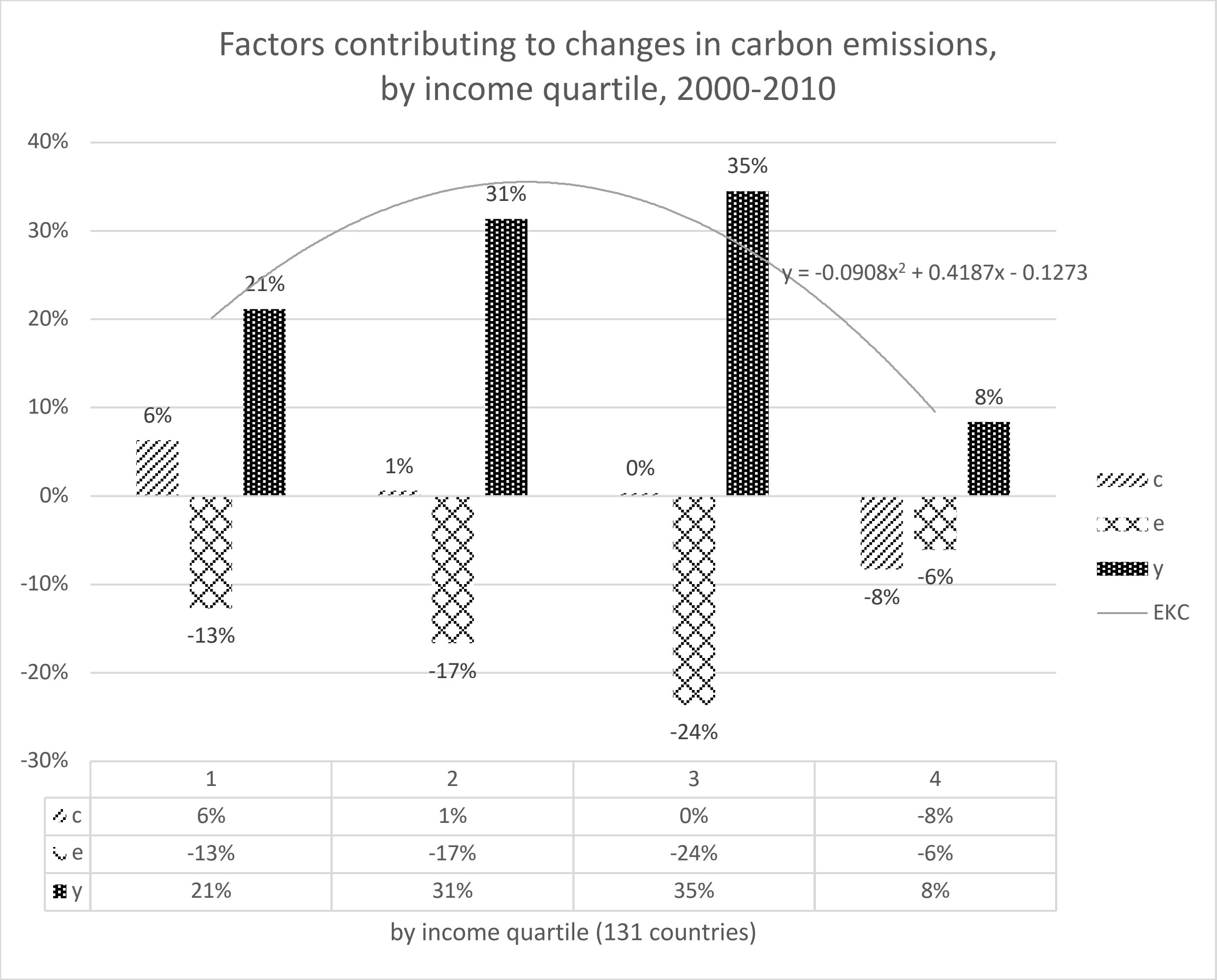
Looking at the results per quartile, we see that the bottom group would have seen emissions rise by 21 percent if it were only for income. However, carbon intensity raised emissions by another 6 percentage points, while energy efficiency had an offsetting effect of 13 percentage points. The total result is a rise of 15 percent in emissions. The second quartile also had a 15 percent rise in emissions, and this shows exactly why we need to study the various factors that produce emissions, since the emissions change was exactly the same as the bottom quartile but the size of the factors was not. In this quartile, income growth had an even greater upward push on emissions. In fact, emissions would have risen by 31 percent if only for income. Carbon intensity added another one percentage point of upward push, but these were offset by the downward push of energy efficiency. So, as we see, income growth does not necessarily result in faster emissions growth, as long as income is sufficiently offset by other factors – this is precisely what we find here in the first and second income quartiles.

Moving on to the third income quartile, the same trend holds true. Income is an even greater positive factor, at 35 percent, but carbon intensity is lower (zero) and energy efficiency is even more important (-24 percent). Then, finally, at the highest income level we see a decline in emissions of six percent. Even though income growth has a positive effect (8%), this is more than offset by improvements in energy efficiency (-6%) and carbon intensity (-8%). Therefore, the results are consistent with the notion of sustainable development, that is, economic growth does not need to engender rising carbon emissions, but rather, as countries grow in income they can offset the upward push on emissions by becoming more energy efficient and decarbonizing the energy supply.

Overall, then, the Shapley decomposition allows us to isolate the effects on emissions of carbon intensity, energy intensity, and per capita income. By sorting the countries by income level, we are able to see how these factors have different impacts at different income levels. As we might expect, increased income is an important and positive factor at lower income levels. At higher income levels, decarbonization and energy efficiency lead to declining emissions even as incomes rise.

The EKC predicts the pattern that we found using Shapley Decomposition with the Pollin identity. Namely, emissions rise from low-income to middle-income, and then fall as income increases further. The literature predicted this pattern, as rising affluence ultimately allows for adoption of cleaner technologies, better pollution controls, preferences for cleaner air and water, more effective institutions with better enforcement of environmental regulations, and structural economic shifts as countries move to more service-oriented economies and import more of their manufactured goods.

Using the decomposition results we obtained above, we can then plot the effect of income on emissions across our four income quartiles in order to assess the shape of the EKC. We see from the graph below that we find the EKC with its expected inverted-U shape. In addition to showing the effects of income on emissions, the graph below shows the contributions of carbon intensity and energy intensity to carbon emissions, and how the effects of each of these three factors (y, c, e) differs by income quartile. While there is an inverted-U shape for the income impact on emissions, there is a U-shaped curve relating energy intensity and emissions, showing that as income increases (between quartiles), the downward pull of improved energy intensity on emissions increases and then decreases (in other words, there is an increasing and then decreasing importance of the impact of energy efficiency on emissions as income rises). The impact of carbon intensity on emissions is monotonically and negatively related to income. In other words, with increased income there is less use of carbon-intensive fuels and the result is a decline in emissions. In the graph as well as in the chart beneath it, we see that carbon intensity goes from positive six percent to negative eight percent as we move from the lowest quartile to the highest.



	1	2	3	4
c	6%	1%	0%	-8%
e	-13%	-17%	-24%	-6%
y	21%	31%	35%	8%

Figure 1: EKC and Pollin Factors by Quartile

Having performed Shapley decomposition on the Pollin factors, we can then use the Shapley values for income in each of our income quartiles to plot the impact of income on emissions. In other words, we can calculate the EKC based on our Shapley values for income, and in doing so we find the following quadratic equation:

$$y = 0.4187x \ -0.0908x^2 - 0.1273 \qquad [15]$$

In the equation above, the dependent variable (y) is the percentage change in per capita carbon emissions (*deltacpc/cpc*) and the independent variable (x) is the Shapley contribution of income, or in other words it is the variable *pcnty* as given above. We could thus rewrite this version of the EKC as:

$$Deltacpc/cpc = 0.4187pcnty - 0.0908pcnty^2 - 0.1273 \qquad [16]$$

The negative coefficient on the squared term shows that the EKC is concave – it is a downward-facing U. Given the income quartiles we have plotted, the vertex is located between the two middle quartiles (technically, at 2.306). The theory behind the EKC predicts exactly this result. As countries move from low-income to middle-income, increased economic output leads to increased emissions. Then as economies continue to grow, emissions decline. In these results, we also see that increased income results in improvements of decarbonization (declining carbon intensity). Improvements in energy efficiency, which offset some of the upward push on emissions caused by income, become increasingly important as income rises in the bottom three quartiles, then become less important in the highest quartile. In the highest income quartile, the most important offsetting factor is decarbonization.

To sum up, in the lowest two income quartiles, income growth has a significant and positive effect on rising emissions, while carbon intensity has a small but positive effect. These are partially offset by the negative effect on emissions of energy efficiency. In the third income quartile, emissions do not grow as fast as they do in the bottom half of the income distribution. Income growth has an equally large and positive effect on emissions, but gains in energy efficiency have a correspondingly larger offsetting effect. In the highest income quartile, income growth has a smaller effect and it is more than offset by the negative push of energy efficiency and carbon intensity, leading to an overall decline in emissions.

5. Conclusion and Policy Implications

This paper weaves together various strands of environmental economics research in order to study the relationship between income and emissions. In formulating policies for low- and middle-income countries in particular, we need to understand the relationship between income and emissions, so we can answer the question of whether it is possible to pursue a growth agenda while also pursuing environmental goals.

Here we try to answer this question by starting with the Pollin Identity, which is a reformulated Kaya Identity. The Pollin identity relates per-capita carbon emissions to per-capita income, energy intensity, and carbon intensity. We can then use a decomposition technique to assess the relative importance of each of the factors on emissions. By using the Shapley Decomposition technique, we evaluate the size and direction for these factors for 132 countries, sorted into income quartiles, for the period 2000-2010. Data is drawn from the WorldBank's "World Development Indicators."

The Shapley technique may be cumbersome when many variables are involved, but is tractable for our purposes. It is ideal and symmetric, meaning that there are no residuals and that the size of each factor's effect is not sensitive to the order in which it was assessed. The Shapley technique is thus useful for our purposes, and using it we find that the income quartiles vary in the size and direction of the income, energy, and emissions factors.

Low- and low-middle income countries had emissions growth of 15% over the period 2000-2010, which was primarily due to income growth but was partially offset by improvements in energy intensity. Upper-middle income countries had slower growth in emissions (11% instead of 15% in the bottom half of the distribution), even though they had slightly higher income growth. Improvements in energy intensity as well as lower carbon intensity resulted in the slightly lower rise in emissions. Finally, the highest income quartile saw a decline in emissions. Even though income growth had an upward push on emissions, this was more than offset by improvements in energy efficiency and decarbonization of the energy supply, resulting in an emissions decline of six percent over the period.

Using the results of the Shapley decomposition, we then use the values for the income factor to plot income against emissions in order to study the size and shape of the Environmental Kuznets Curve (EKC). With our Shapley results, we find that the EKC has the predicted inverted-U shape, with a turning point at the middle of the income distribution. Theory predicts that the EKC would have this shape because as low-income countries grow, they become more industrialized, which leads to more use of energy and greater emissions; but then, as they continue to grow, they shift to lower-emitting service industries and also develop preferences for cleaner air and water and greater environmental protection.

This paper makes various contributions to environmental economics and has important policy implications. First, it uses recent data and a worldwide dataset, thus both expanding and updating the relevance of work that was previously done connecting the EKC and Shapley Decomposition. Second, it reformulates the Kaya Identity into the Pollin Identity by dividing both sides of the Kaya Identity by population. This eliminates population as a control variable, something that may have ethical appeal to researchers and policy makers who would prefer to avoid implications that emissions can be reduced through a decline in population. Third, a unique methodological innovation in this paper is to group countries into income quartiles and then use the results of the Shapley decomposition in order to estimate the EKC. The EKC is indeed found to have an inverted-U shape.

These findings are important from a policy perspective. First, to be clear, they in no way imply that economic growth is the solution to environmental problems. What they do show is that economic growth does not necessarily preclude emissions reductions. But policy is important in ensuring that economic growth is decoupled from energy use, and that a low-carbon growth path is pursued. Both regulatory policies and market incentives can be used to encourage more energy efficiency and energy conservation; likewise, policies can also promote or accelerate the shift to lower-carbon sources of energy, particularly renewable energy such as wind, solar, and geothermal. What we learn by studying the EKC, and by using the Shapley Decomposition technique to evaluate the Pollin Identity, is that it is possible to pursue economic growth without increased emissions, as long as income growth is sufficiently offset by increased energy efficiency and/or decarbonization of the energy mix. The results presented here show that over the period 2000-2010, the EKC exists on a global level – emissions increased with income at the lower end of the income distribution and then declined at the higher end due to increased energy efficiency and a shift to lower-carbon energy sources.

Appendix A: World Bank Data – Names, Definitions, and Sources

Code	Indicator Name	Long definition	Source
EN.ATM.CO2E.PC	CO2 emissions (metric tons per capita)	Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring.	Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, United States.
EN.ATM.CO2E.EG.ZS	CO2 intensity (kg per kg of oil equivalent energy use)	Carbon dioxide emissions from solid fuel consumption refer mainly to emissions from use of coal as an energy source.	Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, United States.
EG.USE.COMM.GD.PP.KD	Energy use (kg of oil equivalent) per $1,000 GDP (constant 2011 PPP)	Energy use per PPP GDP is the kilogram of oil equivalent of energy use per constant PPP GDP. Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport. PPP GDP is gross domestic product converted to 2011 constant international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as a U.S. dollar has in the United States.	IEA Statistics © OECD/IEA 2014 (http://www.iea.org/stats/index.asp), subject to https://www.iea.org/t&c/termsandconditions/
NY.GDP.PCAP.PP.KD	GDP per capita, PPP (constant 2011 international $)	GDP per capita based on purchasing power parity (PPP). PPP GDP is gross domestic product converted to international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as the U.S. dollar has in the United States. GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2011 international dollars.	World Bank, International Comparison Program database.

Appendix B: Shapley Decomposition Results by Country

	2010 GDP PER CAPITA, PPP (CONSTANT 2011 INTERNATIONAL $)	PERCENTAGE CHANGE IN CPC	PERCENTAGE CHANGE IN CPC THAT IS ATTRIBUTABLE TO…		
			y	e	C
CONGO, DEM. REP. [ZAR]	$ 596.32	31%	12%	-9%	27%
NIGER [NER]	$ 820.65	15%	7%	-3%	11%
MOZAMBIQUE [MOZ]	$ 913.99	37%	41%	-40%	36%
ETHIOPIA [ETH]	$ 1,075.55	-16%	63%	-54%	-25%
TOGO [TGO]	$ 1,229.48	-3%	-6%	18%	-16%
ERITREA [ERI]	$ 1,326.12	-57%	-25%	-5%	-27%
ZIMBABWE [ZWE]	$ 1,388.97	-72%	-82%	61%	-52%
HAITI [HTI]	$ 1,502.03	25%	-13%	56%	-18%
BENIN [BEN]	$ 1,759.39	58%	5%	16%	37%
NEPAL [NPL]	$ 1,996.86	15%	24%	-14%	6%
TANZANIA [TZA]	$ 2,111.20	49%	27%	-18%	40%
TAJIKISTAN [TJK]	$ 2,122.99	3%	62%	-83%	24%
SENEGAL [SEN]	$ 2,187.19	37%	10%	5%	22%
BANGLADESH [BGD]	$ 2,451.31	43%	30%	-2%	15%
CAMBODIA [KHM]	$ 2,513.29	44%	47%	-27%	24%
KENYA [KEN]	$ 2,538.58	-9%	17%	-9%	-17%
CAMEROON [CMR]	$ 2,574.97	34%	6%	-19%	47%
COTE D'IVOIRE [CIV]	$ 2,726.29	-41%	-11%	36%	-66%
KYRGYZ REPUBLIC [KGZ]	$ 2,790.17	18%	27%	-21%	12%
GHANA [GHA]	$ 3,083.87	20%	28%	-37%	28%
SUDAN [SDN]	$ 3,240.83	53%	28%	-33%	59%
ZAMBIA [ZMB]	$ 3,277.16	10%	43%	-44%	11%
MOLDOVA [MDA]	$ 3,925.03	30%	45%	-27%	12%
NICARAGUA [NIC]	$ 4,024.23	7%	14%	-11%	4%
UZBEKISTAN [UZB]	$ 4,185.14	-33%	67%	-103%	3%
PAKISTAN [PAK]	$ 4,296.61	20%	18%	-12%	13%
HONDURAS [HND]	$ 4,336.82	25%	19%	2%	5%
YEMEN, REP. [YEM]	$ 4,374.90	25%	9%	10%	5%
INDIA [IND]	$ 4,452.93	29%	49%	-24%	4%
VIETNAM [VNM]	$ 4,486.26	61%	34%	5%	22%
NIGERIA [NGA]	$ 5,122.81	-21%	69%	-60%	-30%
BOLIVIA [BOL]	$ 5,407.47	21%	18%	-10%	13%
CONGO, REP. [COG]	$ 5,595.30	29%	16%	35%	-22%
PHILIPPINES [PHL]	$ 5,638.21	-7%	31%	-48%	10%
MOROCCO [MAR]	$ 6,496.60	32%	30%	-4%	6%
ARMENIA [ARM]	$ 6,507.91	21%	76%	-54%	-1%
GUATEMALA [GTM]	$ 6,667.64	-10%	10%	4%	-25%

GEORGIA [GEO]	$ 6,735.14	38%	60%	-45%	24%
PARAGUAY [PRY]	$ 7,289.51	15%	17%	-11%	9%
EL SALVADOR [SLV]	$ 7,452.56	5%	14%	-12%	3%
MONGOLIA [MNG]	$ 7,708.58	26%	44%	-12%	-6%
UKRAINE [UKR]	$ 7,844.25	2%	50%	-44%	-4%
SRI LANKA [LKA]	$ 8,341.81	17%	40%	-33%	10%
JAMAICA [JAM]	$ 8,365.50	-49%	4%	-52%	-1%
NAMIBIA [NAM]	$ 8,381.88	40%	25%	-4%	20%
INDONESIA [IDN]	$ 8,465.30	31%	32%	-18%	18%
BOSNIA AND HERZEGOVINA [BIH]	$ 9,330.25	34%	33%	-1%	2%
ECUADOR [ECU]	$ 9,352.34	28%	20%	3%	4%
ALBANIA [ALB]	$ 9,373.80	35%	49%	-31%	17%
CHINA [CHN]	$ 9,429.50	56%	65%	-18%	10%
PERU [PER]	$ 9,877.71	41%	33%	-7%	15%
TURKMENISTAN [TKM]	$ 10,031.64	31%	54%	-28%	5%
EGYPT, ARAB REP. [EGY]	$ 10,102.10	17%	27%	10%	-19%
TUNISIA [TUN]	$ 10,543.52	18%	29%	-7%	-4%
COLOMBIA [COL]	$ 10,900.50	16%	25%	-20%	11%
DOMINICAN REPUBLIC [DOM]	$ 11,207.90	-7%	35%	-46%	4%
JORDAN [JOR]	$ 11,256.09	8%	37%	-23%	-7%
MACEDONIA, FYR [MKD]	$ 11,394.04	-44%	33%	-27%	-51%
SOUTH AFRICA [ZAF]	$ 12,086.92	6%	19%	-8%	-5%
COSTA RICA [CRI]	$ 12,659.03	16%	26%	5%	-15%
IRAQ [IRQ]	$ 12,674.15	15%	4%	5%	6%
ALGERIA [DZA]	$ 12,910.84	15%	23%	1%	-8%
BOTSWANA [BWA]	$ 13,119.56	4%	23%	-20%	1%
THAILAND [THA]	$ 13,584.21	33%	32%	3%	-2%
BRAZIL [BRA]	$ 14,405.93	12%	23%	-1%	-10%
PANAMA [PAN]	$ 15,158.77	22%	37%	-20%	5%
BULGARIA [BGR]	$ 15,262.11	11%	52%	-47%	5%
MEXICO [MEX]	$ 15,359.38	1%	3%	2%	-4%
MAURITIUS [MUS]	$ 15,599.00	28%	27%	-9%	9%
BELARUS [BLR]	$ 15,703.11	18%	74%	-59%	4%
AZERBAIJAN [AZE]	$ 15,950.26	-8%	176%	-186%	2%
LEBANON [LBN]	$ 16,277.73	-2%	28%	-32%	1%
GABON [GAB]	$ 16,334.48	41%	-5%	16%	31%
VENEZUELA, RB [VEN]	$ 16,563.40	9%	13%	4%	-8%
TURKEY [TUR]	$ 16,634.16	17%	22%	-5%	0%
URUGUAY [URY]	$ 17,082.41	16%	26%	-2%	-8%
ROMANIA [ROM]	$ 17,354.69	-2%	56%	-48%	-10%
IRAN, ISLAMIC REP. [IRN]	$ 17,517.43	26%	33%	1%	-8%

LATVIA [LVA]	$ 17,982.96	33%	41%	-18%	10%
CUBA [CUB]	$ 18,433.90	31%	43%	-57%	45%
CHILE [CHL]	$ 19,357.47	9%	25%	-17%	0%
KAZAKHSTAN [KAZ]	$ 19,601.09	43%	54%	-11%	0%
CROATIA [HRV]	$ 19,988.74	6%	24%	-15%	-3%
LITHUANIA [LTU]	$ 20,781.99	19%	51%	-41%	10%
MALAYSIA [MYS]	$ 21,101.88	32%	22%	-4%	14%
POLAND [POL]	$ 21,457.43	6%	38%	-25%	-6%
RUSSIAN FEDERATION [RUS]	$ 21,663.64	13%	48%	-35%	0%
HUNGARY [HUN]	$ 22,149.96	-8%	23%	-18%	-13%
ESTONIA [EST]	$ 22,198.88	21%	33%	-13%	1%
SLOVAK REPUBLIC [SVK]	$ 24,503.57	1%	49%	-49%	1%
PORTUGAL [PRT]	$ 27,393.26	-30%	5%	-14%	-22%
MALTA [MLT]	$ 27,906.41	14%	7%	3%	4%
CZECH REPUBLIC [CZE]	$ 28,110.59	-14%	32%	-25%	-20%
SLOVENIA [SVN]	$ 28,388.42	4%	23%	-14%	-5%
LIBYA [LBY]	$ 29,173.61	16%	26%	-17%	8%
GREECE [GRC]	$ 29,259.19	-9%	15%	-16%	-8%
ISRAEL [ISR]	$ 29,652.94	-6%	13%	-8%	-11%
TRINIDAD AND TOBAGO [TTO]	$ 29,913.06	51%	36%	12%	3%
KOREA, REP. [KOR]	$ 30,440.40	17%	35%	-14%	-4%
NEW ZEALAND [NZL]	$ 31,824.13	-17%	14%	-19%	-12%
SPAIN [ESP]	$ 32,975.67	-26%	8%	-19%	-15%
CYPRUS [CYP]	$ 33,747.21	-8%	16%	-22%	-2%
JAPAN [JPN]	$ 34,403.84	-5%	7%	-12%	0%
ITALY [ITA]	$ 35,753.25	-16%	-1%	-4%	-10%
UNITED KINGDOM [GBR]	$ 36,164.00	-17%	10%	-28%	0%
FRANCE [FRA]	$ 36,742.31	-9%	6%	-9%	-6%
ICELAND [ISL]	$ 38,905.47	-25%	17%	33%	-75%
FINLAND [FIN]	$ 39,424.85	12%	12%	-4%	4%
BAHRAIN [BHR]	$ 40,237.60	-52%	-14%	-8%	-29%
GERMANY [DEU]	$ 40,664.90	-10%	10%	-13%	-7%
BELGIUM [BEL]	$ 40,698.04	-12%	10%	-13%	-10%
CANADA [CAN]	$ 40,773.07	-19%	10%	-21%	-8%
AUSTRALIA [AUS]	$ 41,363.22	-3%	16%	-16%	-3%
SWEDEN [SWE]	$ 42,897.56	1%	15%	-14%	0%
AUSTRIA [AUT]	$ 42,964.59	4%	10%	3%	-9%
DENMARK [DNK]	$ 42,997.37	-15%	3%	-3%	-15%
SAUDI ARABIA [SAU]	$ 44,246.82	27%	19%	12%	-5%
IRELAND [IRL]	$ 44,683.73	-23%	13%	-28%	-8%
NETHERLANDS [NLD]	$ 45,842.52	5%	8%	0%	-3%

OMAN [OMN]	$ 46,832.31	49%	4%	46%	-1%
HONG KONG SAR, CHINA [HKG]	$ 48,107.71	-18%	39%	-43%	-13%
UNITED STATES [USA]	$ 49,372.80	-16%	8%	-20%	-3%
SWITZERLAND [CHE]	$ 54,182.85	-10%	10%	-14%	-6%
UNITED ARAB EMIRATES [ARE]	$ 57,406.74	-83%	-87%	32%	-28%
NORWAY [NOR]	$ 62,945.99	26%	6%	9%	11%
BRUNEI DARUSSALAM [BRN]	$ 71,941.61	16%	-4%	16%	3%
SINGAPORE [SGP]	$ 72,055.46	-358%	99%	-72%	-386%
KUWAIT [KWT]	$ 73,695.13	7%	-1%	8%	-1%
LUXEMBOURG [LUX]	$ 90,790.83	13%	11%	-3%	5%
QATAR [QAT]	$ 127,670.61	-37%	18%	-37%	-18%
WORLD [WLD]*	**$ 13,070.21**	**13%**	**22%**	**-11%**	**3%**

*Note here that "World" is one of the variables downloaded from the WDI database and is not necessarily an average of the countries in this table.

References

Agnolucci, P., Ekins, P., Iacopini, G., Anderson, K., Bows, A., Mander, S., & Shackley, S. (2009). Different scenarios for achieving radical reduction in carbon emissions: A decomposition analysis. *Ecological Economics*, 1652-1666.

Albrecht, J., Francois, D., & Schoors, K. (2002). A Shapley decomposition of carbon emissions without residuals. *Energy Policy*, 727-736.

Allard, A., Takman, J., Sallah Uddin, G., & Ahmed, A. (2018). The N-shaped environmental Kuznets curve: an empirical evaluation using a panel quantile regression approach. *Environmental Science and Pollution Research*, 5848-5861.

Al-Mulali, U., & Ozturk, I. (2016). The investigation of environmental Kuznets curve hypothesis in the advanced economies: The role of energy prices. *Renewable and Sustainable Energy Reviews*, 1622-1631.

Ang, B. (2004). Decomposition analysis for policymaking in energy: which is the preferred method? *Energy Policy*, 1131-1139.

Ben Jebli, M., Ben Youssef, S., & Ozturk, I. (2016). Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries. *Ecological Indicators*, 824-831.

Bilgili, F., Kocak, E., & Bulut, U. (2016). The dynamic impact of renewable energy consumption on CO2 emissions: A revisited Environmental Kuznets Curve approach. *Renewable and Sustainable Energy Reviews*, 838-845.

Carson, R. T. (2010). The Environmental Kuznets Curve: Seeking Empirical Regularity and Theoretical Structure. *Review of Environmental Economics and Policy*, 3-23.

De Cian, E., Schymura, M., Verdolini, E., & Voigt, S. (2013). *Energy Intensity Developments in 40 Major Economies: Structural Change or Technology Improvement?* Milan: Fondazione Eni Enrico Mattei (FEEM).

Deutch, J. M. (2011). Energy and Climate Change. In *The Crisis in Energy Policy.* Cambridge, MA: Harvard University Press.

Dinda, S. (2004). Environmental Kuznets Curve Hypothesis: A Survey. *Ecological Economics*, 431-455.

Dobes, L., Jotzo, F., & Stern, D. I. (2014). The Economics of Global Climate Change: A Historical Literature Review. *Review of Economics*, 281-320.

Farhani, S., Mrizak, S., Chaibi, A., & Rault, C. (2014). The environmental Kuznets curve and sustainability: A panel data analysis. *Energy Policy*, 189-198.

Grossman, G. M., & Krueger, A. B. (1991). *Environmental impacts of a North American free trade agreement.* National Bureau of Economic Research.

Grossman, G. M., & Krueger, A. B. (1995). Economic Growth and the Environment. *The Quarterly Journal of Economics*, 353-377.

Han, L., Xu, X., & Han, L. (2015). Applying quantile regression and Shapley decomposition to analyzing the determinants of household embedded carbon emissions: Evidence from urban China. *Journal of Cleaner Production*, 219-230.

Hoekstra, R., & van den Berg, J. (2003). Comparing structural and index decomposition analysis. *Energy Economics*, 39-64.

Inchauste, G., Azevedo, J. P., Essama-Nssah, B., Oliviero, S., Nguyen, T. V., Saavedra-Chanduvi, J., & Winkler, H. (2014). *Understanding Changes in Poverty. Directions in Development.* Washington, D.C.: World Bank.

Kaika, D., & Zervas, E. (2013). The Environmental Kuznets Curve (EKC) theory - Part A: Concept, causes, and the CO2 emissions case. *Energy Policy*, 1392-1402.

Kerr, D., & Mellon, H. (2012). Energy, population and the environment: exploring Canada's record on CO2 emissions and energy use relative to other OECD countries. *Population and the Environment*, 257-278.

Kwakwa, P. A., & Adu, G. (2016). Effects of Income, Energy Consumption, and Trade Openness on Carbon Emissions in Sub-Saharan Africa. *The Journal of Energy and Development*, 86-117.

Lipford, J. W., & Yandle, B. (2010). Environmental Kuznets curves, carbon emissions, and public choice. *Environment and Development Economics*, 417-438.

Nakicenovic, N., & Swart, R. (. (2000). *Emissions Scenarios: Summary for Policymakers.* Geneva, Switzerland: IPCC.

O'Mahony, T. (2013). Decomposition of Ireland's carbon emissions from 1990 to 2010: An extended Kaya identity. *Energy Policy*, 573-581.

Ozokcu, S., & Ozdemir, O. (2017). Economic growth, energy, and environmental Kuznets curve. *Renewable and Sustainable Energy Reviews*, 639-647.

Rafaj, P., Amann, M., Siri, J., & Wuester, H. (2014). Changes in European green gas and air pollutant emissions 1960-2010: decomposition of determining factors. *Climatic Change*, 477-504.

Raymond, L. (2004). Economic Growth as Environmental Policy? Reconsidering the Environmental Kuznets Curve. *Journal of Public Policy*, 327-348.

Riti, J. S., Song, D., Shu, Y., & Kamah, M. (2017). Decoupling CO2 emission and economic growth in China: Is there consistency in estimation results in analyzing environmental Kuznets curve? *Journal of Cleaner Production*, 1448-1461.

Shapley, L. (1953). A value for n-person games. *Contributions to the Theory of Games, 2*(28), 307-317.

Su, B., & Ang, B.W. (2012). Structural decomposition analysis applied to energy and emissions: Some methodological developments. *Energy Economics*, 177-188.

Tiba, S., & Omri, A. (2017). Literature survey on the relationships between energy, environment and economic growth. *Rnewable and Sustainable Energy Reviews*, 1129-1146.

Yang, G., Sun, T., Wang, J., & Li, X. (2015). Modeling the nexus between carbon dioxide emissions and economic growth. *Energy Policy*, 104-117.

Zhang, Y., Zhang, J., Yang, Z., & Li, S. (2011). Regional differences in the factors that influence China's energy-related carbon emissions, and potential migation strategies. *Energy Policy*, 7712-7718.