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A cross-country analysis of aggregate energy and carbon intensities

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Abstract

An update on the study by Ang [Energy Economics 9 (1987) 274–286] shows substantial changes in the relationship between energy consumption and national output across world countries from 1975 to 1997. While the ratio of commercial energy consumption to national output increases across countries as per capita income increases in 1975, the converse is observed in 1997. The cross-country energy elasticity has also dropped from values well above unity to below or close to unity. Using the 1997 data, the relationship between CO_2 emissions and national output across countries is studied and the results show some interesting differences from that between energy consumption and national output.

Keywords: Energy-GNP correlation; Aggregate energy intensity; Aggregate CO_2 intensity; Energy elasticity; CO_2 elasticity

1. Introduction

The relationship between energy consumption (or CO_2 emissions) and national output is a topic that has attracted a great deal of attention. Among all the theories, the most famous one is the environmental Kuznets curve (EKC), an inverted-U shaped curve proposed by Kuznets (1955). Schurr et al. (1960) found that this shape exists in American energy use and economic output. Later on, many studies have appeared in the literature, e.g. Jänicke et al. (1989), Grossman and Krueger (1991), a special issue of the journal *Ecological Economics* 25 (1998) and Andreoni and Levinson (2001). To make it more practical, some researchers have attempted to refine the EKC hypothesis. Shafik (1994) and Grossman and Krueger (1995) found evidence of an N-shaped curve in some developed countries, which shows that a re-materialisation phase exists after dematerialisation.

However, the EKC hypothesis has encountered intense criticisms from researchers. Stern et al. (1996) pointed out the assumption of unidirectional causality from growth to environmental quality as one of the major problems of the EKC. Some researchers have switched from this simple deterministic and predictive approach to dynamic studies. For instance, Unruh and Moomaw (1998) used a dynamic model to study CO_2 emissions in several countries and concluded that CO_2 emissions trajectories exhibit "punctuated equilibrium". Jesús and Miquel (2003) supported this "punctuated equilibrium" by studying energy intensity evolution. Similarly, Müller (2004) used a dynamic model to describe economies as non-continuous and non-predictive systems and treated policy as a social steering mechanism.

Noting that the underlying forces that drive the evolution of energy consumption or CO_2 emissions cannot be economic growth alone, some researchers have attempted to study factors contributing to changes in the relationship. The technique of decomposition analysis has been developed to quantify the contributions arising from factors such as changes in economic activity mix and activity energy intensity, and numerous studies have been reported (Ang and Zhang, 2000). In a recent study, Welsch and Ochsen (2005) pointed out that the volatility of energy intensity in West Germany is the

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result of factor substitution, biased technological change and trade.

From the massive literature available on this subject, it can be seen that there is no consensus that can be drawn. The need for further empirical analysis remains pertinent. The main purpose of this paper is to study the relationship empirically.

2. Data and statistical analysis

We define the aggregate energy intensity (AEI) as the ratio of national energy consumption to national output given by gross domestic product (GDP) or gross national product (GNP). The aggregate energy intensity, or traditionally called the energy-output ratio, has often been used as a measure of the "effectiveness" of energy use or as a proxy of the economy-wide "energy efficiency" at the most aggregate level. We also define the aggregate CO_2 intensity (ACI) as the ratio of national CO_2 emissions to national output. Both the aggregate energy intensity and the aggregate CO_2 intensity are important performance indicators in international energy and energy-related CO_2 emission studies.

A cross-country analysis of energy and national output correlation using the 1975 data for 100 countries was reported in Ang (1987). It was found that as per capita income increases across countries, the aggregate energy intensity, measured using commercial energy consumption and purchasing power parity (PPP) based GDP, also increases. There exists certain disparity on energy consumption and GDP correlation with higher income countries consuming disproportionately more energy per unit of real output. The study also gives estimates of the cross-country energy elasticity defined as the percentage change in per capita energy consumption for each percentage change in per capita income across countries. The estimates for commercial energy consumption exceed unity through the whole of the 1975 per capita income range of the 100 countries.

This study is an update on the study by Ang (1987) which we shall refer to as the "1975 study". Using 1997 data, we report the shifts in cross-country energy-output relationship 22 years after 1975. In addition, we also use the 1997 data to conduct a cross-country analysis on the relationship between CO_2 emissions and national output which is not covered in the 1975 study. In the same vein, we define cross-country carbon elasticity as the percentage change in per capita CO_2 emissions for each percentage change in per capita income across countries. In this study, we limit our analysis to commercial energy consumption only. The term energy consumption refers to only commercial energy sources and does not include non-commercial energy sources.

The key variables and abbreviations are summarized in Table 1. All the data used in this study are for 1997. The variables and the data sources are: GNP and population from World Bank (1999), energy consumption from World Bank (2000), and CO_2 emissions from World Bank (2001). CO_2 emissions are anthropogenic emissions resulting from fossil fuel combustion and cement manufacturing. Data for the above variables were collected for a total of 104 countries with a population more than two million in 1997.

The 1975 study was based on 100 market economies with a population exceeding two million. The 104 countries for 1997 include centrally planned countries and countries which in 1975 were part of centrally planned countries. A total of 80 countries appear in both the 1997 and 1975 lists. In order to have a more complete picture for 1997 as well as to make meaningful comparisons between 1997 and 1975, we use two datasets for 1997: Dataset A covers all the 104 countries while Dataset B covers only the 80 countries that appear in the 1975 study. Countries included in Dataset A but not in Dataset B are primarily Eastern European countries, Russia and centrally planned countries such as China and Vietnam.

A number of other differences exist between the present and the 1975 study arising from data limitations. The 1975 study used GDP and population data taken from United Nations publications and the analysis was

Table 1
Summary of key variables, abbreviations and definitions

Notation	Meaning/definition
E	Per capita energy consumption
C	Per capita CO_2 emissions
Y	Per capita GNP (1997 data) and per capita GDP (1975 data) in current US dollars adjusted for the purchasing power parity (PPP) in the respective years
AEI	Aggregate energy intensity given by E/Y
ACI	Aggregate CO_2 intensity given by C/Y
ACEF	Aggregate CO_2 emission factor given by C/E
α_E	Cross-country energy elasticity defined as $(\mathrm{d}E/E)/(\mathrm{d}Y/Y)$
α_C	Cross-country CO_2 elasticity defined as $(\mathrm{d}C/C)/(\mathrm{d}Y/Y)$

conducted based on two sets of GDP data, i.e. GDP in 1975 US dollars with and without adjustment for PPP. In this study, the analysis is based on GNP data. For conciseness, we shall present only the results obtained using PPP-based GNP data for 1997 (in 1997 prices) and PPP-based GDP data for 1975 (in 1975 prices), and use the term "income per capita" generally to refer to per capita GNP or GDP. In the 1975 study, electricity from hydro and nuclear sources was converted into oil equivalents using a notional thermal efficiency of 30 percent and some adjustments were made to coal consumption to give its "petroleum replacement value". In the present study, the data taken from World Bank (2000) are based on a notional thermal efficiency of 33 percent for nuclear electricity and 100 percent for hydroelectricity and no adjustment is made to coal consumption.

We follow closely the model specifications and statistical analysis reported in the 1975 study. Details of the regression runs for 1997 are summarized in Table 2, which corresponds to Table 3 in Ang (1987). We report the main findings related to the relationship between energy consumption and national output in Section 3 and that between CO_2 emissions and national output in Section 4. All the results are shown graphically from Figs. 1 to 7. In these figures where the data collected are plotted, they are for the 104 countries (i.e. Dataset A) unless otherwise stated. From Figs. 1 to 5, the fitted regression lines for 1997 using Datasets A and B are plotted separately.

3. Cross-country analysis for energy consumption

Fig. 1 shows the 1997 energy consumption per capita when plotted against income per capita for the 104 countries. A simple regression run using Model 1 gives a constant cross-country energy elasticity of $\alpha_E = 0.78$ (all the regression models referred to are given in Table 2). When Dataset B is used, we have $\alpha_E = 0.81$ (see Model 1B). The corresponding estimate for 1975 in Ang (1987) is 1.80. We may conclude that for the same percentage variation in per capita income, the percentage variation in per capita energy consumption across countries has decreased drastically from 1975 to 1997.

The fitted lines for 1997 in Fig. 1 is based on a quadratic model (Model 2 and Model 2B) which allows non-linear relationship between energy consumption per capita and income per capita to be captured. The dotted line in the figure is the corresponding quadratic

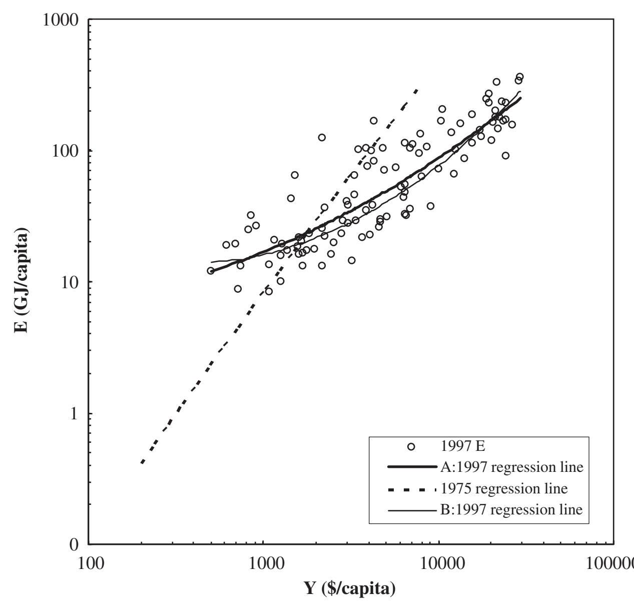

Fig. 1. Energy consumption per capita (E) versus income per capita (Y), 1975 and 1997.

Table 2
Regression models and results using the 1997 data (P-values for the coefficient estimates are given in parenthesis)

Model[a]	Dependent variable	Constant	$\ln Y$	$(\ln Y)^2$	$\bar{R}^2$
1	$\ln E$	−2.654 (0.000)	0.782 (0.000)	—	0.735
1B	$\ln E$	−2.972 (0.000)	0.808 (0.000)	—	0.823
2	$\ln E$	2.783 (0.357)	−0.526 (0.467)	0.077 (0.072)	0.741
2B	$\ln E$	8.203 (0.002)	−1.884 (0.003)	0.159 (0.000)	0.857
3	$\ln C$	−8.860 (0.000)	1.143 (0.000)	—	0.725
4	$\ln C$	−23.124 (0.000)	4.575 (0.000)	−0.203 (0.001)	0.750
5	$\ln(C/E)$	−18.999 (0.000)	5.100 (0.000)	−0.280 (0.000)	0.532

[a]Dataset A is used in all the regression runs except for Models 1B and 2B where Dataset B is used.

regression fit for 1975 reproduced from Ang (1987). The decrease in the cross-country energy elasticity is clearly shown by the slopes of the fitted lines, i.e. the slopes of the 1997 regression lines are less steep compared to those of 1975. For 1997, a distinct feature of the fitted regression lines is that its gradient increases with per capita income. This indicates that for the same percentage change in per capita income, the percentage change in per capita energy consumption is greater in the higher per capita income range. This however is not the case for 1975.

Fig. 2 shows how the aggregate energy intensity changes across countries. The fitted lines have been derived from Fig. 1. The differences between 1997 and 1975 are striking. While the aggregate energy intensity increases as per capita income increases across countries in 1975, the converse is observed in 1997. The plots show that the energy requirements to generate a unit of output in industrial countries are much higher than those in the developing countries in 1975, but the converse is the case in 1997. A possible explanation is that, during the period 1975–1997, significant and diverging changes in energy consumption took place between the industrial countries and the developing countries. While the aggregate intensities for the industrial countries have been declining, those for the developing countries have either been increasing or remained little change. From Fig. 2, it can be seen that there is greater uniformity in the aggregate intensity across the whole income range in 1997 compared to 1975. Interestingly, the fitted aggregate energy intensity lines for both years do not have a peak. Instead, the 1997 fitted line for Dataset B seems to reach a minimum around \$9000 and increases thereafter.

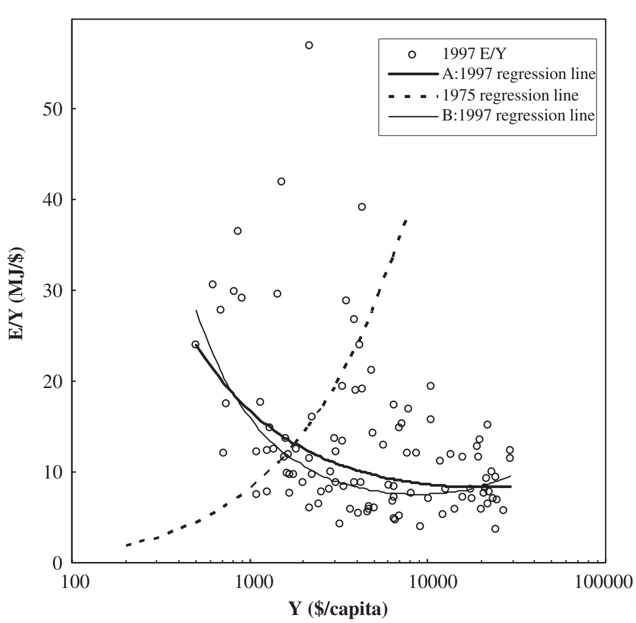

Fig. 2. Aggregate energy intensity (AEI) versus income per capita (Y), 1975 and 1997.

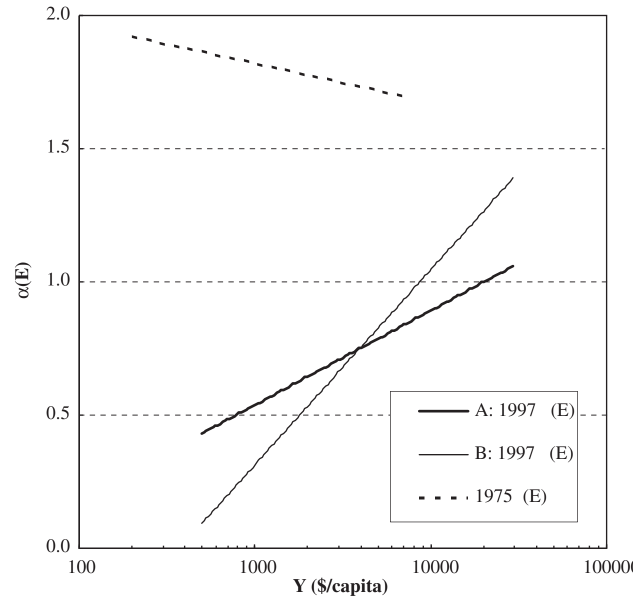

Fig. 3. Cross-country energy elasticities (α_E) versus income per capita (Y), 1975 and 1997.

The cross-country energy elasticities are shown in Fig. 3. They have been derived from Model 2 and Model 2B. Their values are dependent on per capita income and the mathematical details can be found in Ang (1987). For ease of interpretation, one may use the reference point that an elasticity exactly equals to unity implies per capita energy consumption changes at the same rate as per capita income and there would be no change in the aggregate energy intensity. The following two changes from 1975 to 1997 are noteworthy. First the 1975 estimates of the elasticity are greater than unity (between 1.5 and 2) through the whole per capita income range while those of 1997 are below unity except at the very high per capita income range. Second, as per capita income increases, the elasticity estimate decreases in 1975 but increases in 1997.

4. Cross-country analysis for CO_2 emissions

Using the 1997 Dataset A, a similar study for CO_2 emissions has been conducted. No comparisons are made with the situation in 1975 as the study by Ang (1987) does not cover CO_2 emissions.

Fig. 4 shows the CO_2 emissions per capita versus income per capita plot. A simple regression run gives a constant cross-country CO_2 elasticity of $\alpha_C = 1.14$ (Model 3). This is larger than the corresponding estimate for energy demand of $\alpha_E = 0.78$ (Model 1). The relationship can be better captured by a non-linear model (Model 4) which gives that fitted regression line in Fig. 4. A comparison between Figs. 4 and 1 shows

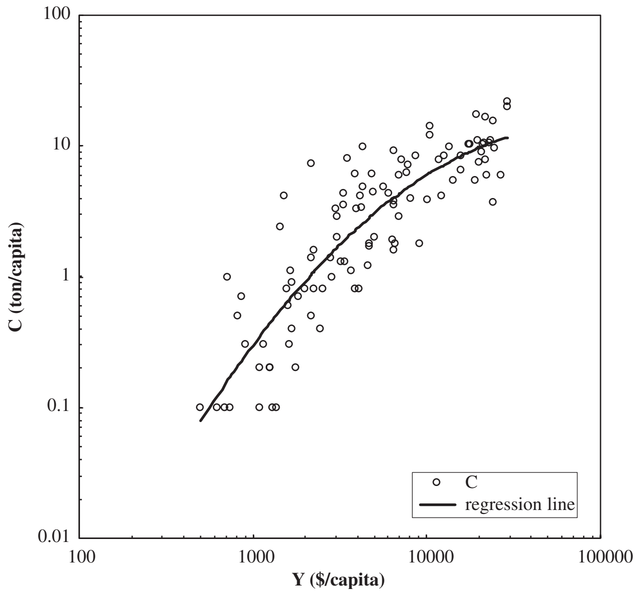

Fig. 4. CO_2 emissions per capita (C) versus income per capita (Y), 1997.

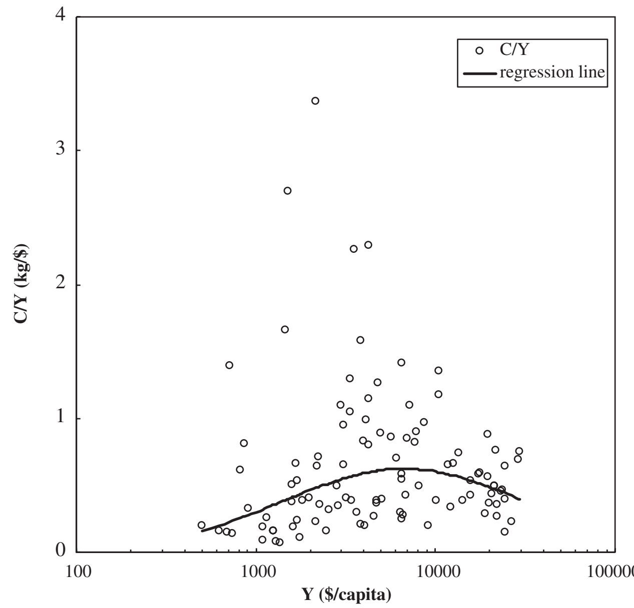

Fig. 5. Aggregate CO_2 intensity (ACI) versus income per capita (Y), 1997.

different shapes for the two fitted lines; as per capita income increases, the gradient increases in the case of energy consumption but it decreases in the case of CO_2 emissions. This means cross-country variation in per capita energy consumption increases as per capita income increases, while that in per capita CO_2 decreases as per capita income increases.

Fig. 5 shows the aggregate CO_2 intensity versus income per capita plot and the regression fit. It may be seen that the aggregate CO_2 intensity increases as income per capita increases, reaching a peak and decreases slowly thereafter. This shape is very different from that for the aggregate energy intensity shown in Fig. 2. Compared to high income countries, low income countries have a higher aggregate energy intensity but the converse is true to a large extent in the case of aggregate CO_2 intensity.

The cross-country CO_2 elasticity estimates derived from Model 5 are plotted in Fig. 6. The elasticity decreases as per capita income increases and it is unity at a per capita GNP of about \$7000. For a given percentage variation in per capita income, the percentage variation in per capita CO_2 decreases across countries as per capita income increases. The 1997 cross-country energy elasticity estimates for energy consumption shown in Fig. 3 is reproduced in Fig. 6. In the low per capita income range, estimates of the CO_2 elasticity exceed those of energy elasticity but the converse is the case in the high per capita income range. For a given percentage change in per capita income, there would be greater percentage variations in CO_2

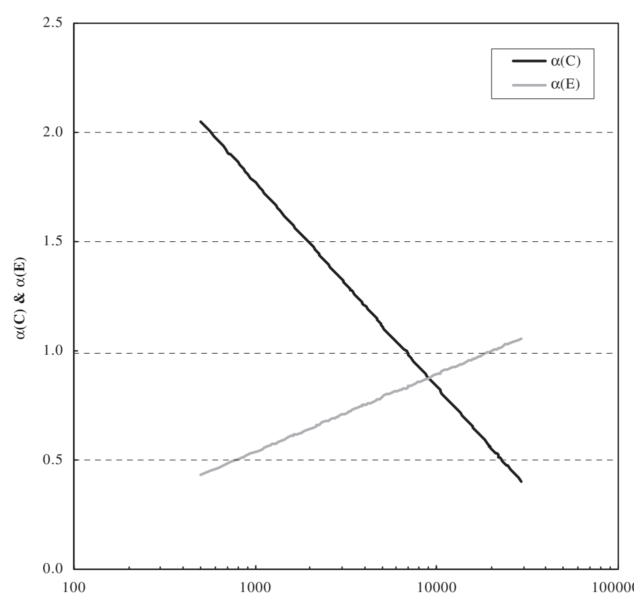

Fig. 6. Cross-country CO_2 elasticity (α_C) and α_E versus income per capita (Y), 1997.

emissions than in energy consumption in the low per capita income range, while the converse is true in the high per capita income range.

Fig. 7 shows the derived aggregate CO_2 emission factor (ACEF) obtained by dividing total CO_2 emissions by total energy consumption for each country. This derived factor is likely to be an overestimate of the

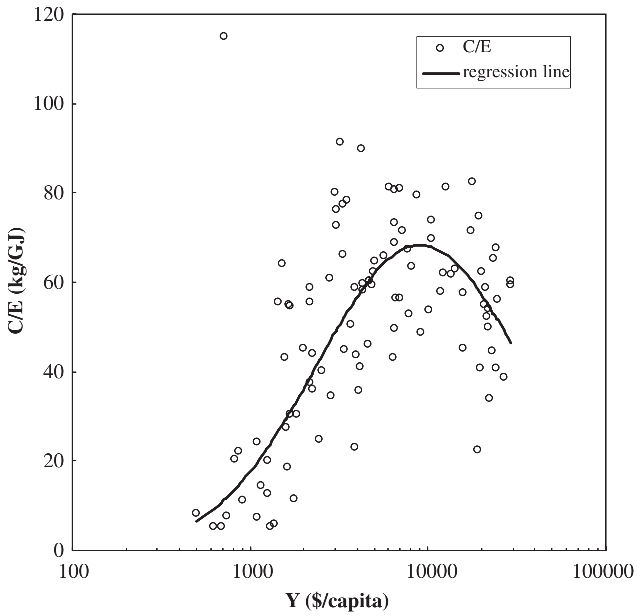

Fig. 7. Aggregate carbon emission factor (ACEF) versus income per capita (Y), 1997.

actual ACEF as the CO_2 emissions include emissions from fossil fuel combustion and cement manufacturing. The factor is generally low for the low income countries and very high for countries with per capita income of around $9000. The variations over the whole income range are fairly substantial. These variations are the underlying factor leading to the differences observed between the correlation of energy consumption and national output and that of CO_2 emissions and national output given by their respective aggregate intensities and elasticities. For instance, the aggregate CO_2 intensity can be expressed as the product of the aggregate energy intensity and the aggregate CO_2 emission factor, i.e. $C/Y = (E/Y)(C/E)$. Thus the behaviour of C/Y and that of E/Y, respectively shown in Figs. 5 and 3, would be very similar if the aggregate CO_2 emission factor (C/E) remains little change across countries. Since variations in fuel carbon emission factors are generally not very substantial across countries, especially for petroleum products and national gas, variations in the aggregate CO_2 emission factor, such as those shown in Fig. 7, should arise mainly from variations in fuel mix in energy consumption (and in cement production).

Figs. 5 and 7 show threshold values ($7000 and $9000) for per capita income above which the aggregate carbon intensity and the aggregate carbon emission factor begin to decline respectively. Using time-series data for 16 OECD countries, Unruh and Moomaw (1998) obtained a threshold range of $7900 to $14,500 per capita income (1985 US$) above which per capita CO_2 emissions begin to decline. There may be some consistency in their findings and the findings in this study with regard to the "threshold issue" but further analysis is needed since the data sets used and the indicators concerned are different.

5. Conclusion

We have revisited the issue of the relationship between energy consumption and national output across world countries using the data of 1997. As expected, there is a good correlation between per capita energy consumption and per capita income and the simple energy elasticity is found to be around 0.8. This estimate is much smaller than that of 1.8 for 1975. Given the same percentage variation in per capita income across countries, the variation in per capita energy consumption has decreased fairly substantially over the 22-year period.

The changes that have taken place in the case of the aggregate energy intensity are also substantial. While the aggregate energy intensity increases as per capita income increases across countries in 1975, the converse is observed for 1997. The aggregate energy intensity of an industrial country would be about three times that of a low income developing countries in 1975, but it would only be half of that of the latter in 1997. It appears that while the high income countries have been able to achieve significant reductions in the growth of energy consumption for each percentage growth of economic growth, the growth in energy consumption has remained high as compared to economic growth in the low income countries.

In 1997, while the correlation between CO_2 emissions per capita and income per capita is a positive one across countries, which is similar to that between energy consumption and income, the cross-country variations in the aggregate CO_2 intensity are fairly different from those in the aggregate energy intensity. In particular, the aggregate CO_2 intensity increases as per capita incomes increase across countries, reaches a peak and decreases thereafter, which fits the EKC model fairly well. In contrast, the aggregate energy decreases as per capita income increases through the whole per capita income range.

Compared to cross-country variations in the aggregate energy intensity, cross-country variations in the aggregate CO_2 intensity are larger in the low per capita income range but smaller in the high per capita income range. This disparity is likely to arise from variations in fuel mix in energy consumption which are captured by large and systematic variations in the aggregate CO_2 emission factor across countries.

The empirical results obtained show that the relationship between energy consumption and national output across countries is a highly dynamic one. It is affected by a number of factors and cannot be easily explained by a simple model such as the EKC model. As to the relationship between CO_2 emissions and national output, the EKC model appears to be applicable for the aggregate CO_2 intensity in 1997. In conclusion, a dynamic model is more appropriate than a static one such as the EKC to describe the relationship between energy consumption (or CO_2 emissions) and national output.

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