Autonomous Energy Efficiency Improvements: Relevance, Use, and Empirical Basis for Global Climate Change Policy Analysis

by

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Abstract

This thesis critically examined the autonomous energy efficiency improvement (AEEI) parameter which is used in economic cost models for global warming policy analysis. Even though the AEEI significantly affects the estimates of future carbon emisions, the parameter has not been rigorously defined and its value is set almost arbitrarily. This thesis presents a more rigorous and complete definition of the AEEI. The AEEI is shown to take on different meanings in the different models, reflecting structural differences in the models. The parameter was estimated for twenty-three countries for the period 1951-1990 using simple econometric techniques. The estimation suggests that the AEEI is statistically significant and negative. Interestingly, the analysis also suggests that price effects are insignificant over this long time period. Other relevant empirical studies are shown to be inadequate guides for selecting the AEEI.

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Chapter 1

Introduction

1.1 Motivation

The formulation of policies which address the issue of global warming rely in part on economic cost models. These economic models reveal projections of radiative forcing[1] emissions, also known as greenhouse gases (GHGs). Carbon dioxide (CO_2) is the principal greenhouse gas, accounting for about 60% of the GHGs entering the atmosphere. Carbon dioxide is produced when fossil fuels are burned.[2] Thus, one strategy for lessening the threat of global warming is to reduce fossil fuel use. This strategy comes with a price tag. The economic models can be used to estimate this cost.

These models include a parameter known as the *autonomous energy efficiency improvement* rate (AEEI). The AEEI is generally understood to describe changes in energy demand in which technological development is particularly important. The value selected for this parameter is quite significant to model results. Relatively small changes of the parameter determine markedly different model results.

There is remarkably little agreement upon a specific value or even an acceptable range for the AEEI. This uncertainty is a severe handicap in predicting future energy

[1] "Radiative Forcing" is the name given to the effect by which gases alter the energy balance of the Earth-atmosphere system. See [26] for more detail on the scientific analysis of global climate change.

[2] Increases of carbon dioxide in the atmosphere are also attributed to deforestation.

Table 1.1: Comparison of AEEI value selected for different models

Model:	United States	Other OECD	Former Soviet Union	China	Rest of World
ERM	1.0	1.0	1.0	1.0	1.0
GREEN	1.0	1.0	1.0	1.0	1.0
IEA	-1.1	-1.1	..	..	..
MR	0.5	0.5	0.25	1.0	0.0
WW	0.0	0.0	0.0	0.0	0.0

consumption and the carbon emissions path. The AEEI has been set to different values in various economic models, ranging from -1.1[3] to 0[4] to 1.0[5]. Some of the models vary the parameter over time[6] and/or across regions, while other modellers choose to keep the parameter constant over all time and across all geographic regions. Table 1.1 shows the AEEI selection for five of the cost models.

The significance of this parameter can be demonstrated by a simple sensitivity analysis of the simulation results. Three models were run at two different levels for the AEEI — 1% and 0.5%. The model results are tabulated in Table 1.2. The two settings produced dramatically different results for the models which predict to the year 2100. The Edmonds-Reilly model predicts carbon emissions for the year 2100 which differ by 46% under the different AEEI settings.[7] The carbon emissions estimated by the Manne-Richels model, which also predicts to the year 2100, are different by 34%. GREEN, the model which predicts only to the year 2050, yields only slight differences under the two settings; carbon emissions differ by 13%.

[3]This value was selected in the IEA model [55].

[4]Whalley-Wigle model [56].

[5]OECD GREEN model [10] and the Edmonds-Reilly model [16].

[6]Edmonds and Reilly[16] and [17] originally chose to increase the technological improvement factor for energy by a constant additive factor every year. Also, while Manne and Richels [36, p.33] assume different initial AEEI values for different regions, all AEEI values converge linearly with time to 0.5 by the year 2050.

[7]The difference in CO_2 levels is twenty billion tons of carbon, equivalent to over three times the 1990 world emission level.

Table 1.2: Worldwide CO_2 Emissions for "Business-as-Usual" case predicted by three models. The three models were run at two different settings for the AEEI, 1% and 0.5%. Results are shown for the year indicated in parentheses.

	Predicted Worldwide CO_2 Emissions (Billion tons of Carbon)		
AEEI	Edmonds-Reilly (2100)	GREEN (2050)	Manne-Richels (2100)
1%	22.6	19.0	26.0
0.5%	41.6	21.8	39.6

1.2 Elements of the Problem

The difficulty in selecting values for the AEEI stems from two sources. First, there are different understandings for what the AEEI encompasses. Second, there have been relatively few econometric studies which attempt to estimate the parameter. Given that the AEEI is such an important parameter in the economic models, it would be worthwhile to develop a framework for understanding the AEEI and to analyze the empirical evidence within this framework.

1.3 Outline

This thesis will present a more complete description of the AEEI and will analyze empirical studies to determine how they can guide selection of the AEEI. The purpose of this research is to clarify existing misunderstandings about the AEEI and to provide a framework for future discussions on the AEEI. Chapter 2 will provide a more complete and rigorous definition for the AEEI. Chapter 3 will analyze data on energy consumption and national income using simple econometric techniques. Chapter 4 will review the econometric literature to show why past empirical studies have not been useful to guide selection of the AEEI. Chapter 5 will summarize the conclusions of this research.

Chapter 2

Understanding the AEEI

2.1 Rationale for AEEI Setting in Cost Models

The modellers assume values for the technological change parameter by using their best judgment. Generally, little information is offered to support the parameter selection. The documentation of the economic models generally states that the parameter should be included, but different reasons are offered for the parameter value chosen.

2.1.1 Edmonds and Reilly

Edmonds and Reilly[1] justify their inclusion of a technological progress parameter[2] "to account for the fact that technological progress has acted to conserve energy even when energy prices fell"[16, p.84]. They assume in their initial 1983 analysis that the technological progress parameter increases with time in the industrial sector of the OECD regions by a constant additive factor of 0.01, beginning with 1.0 in 1975, and increasing to 1.75 in 2050. They further assume that in the residential/commercial and transport sectors, technological change occurs only in response to price changes.[3]

[1] The Edmonds-Reilly model is documented in [16] and [17].

[2] Edmonds and Reilly use the notation, TECH. They describe TECH as the level of technological progress. Computationally, demand for each secondary fuel is proportional to 1/TECH[16, p.84]. They further explain that TECH can be interpreted as the amount of energy service derived from a unit of energy[17, p.27].

[3] When technological change only occurs in response to price changes, TECH is set to 1.0.

In the non-OECD regions, the technological change coefficient increases by a constant additive factor of 0.004, from 1.00 in 1975 to 1.30 in 2050. These values were assumed by Edmonds and Reilly for their initial 1983 base case. Subsequent simulations produced in 1990 for the OECD Model Comparisons Project [13] employed a value of 1.0 for all regions.

2.1.2 OECD GREEN

The GREEN modellers chose to set the energy efficiency parameters to 1.0 for all regions and all times. While the technical reference manual offers no explanation for this setting, the description of the model in [9], which presents the basic specification and structure of GREEN, provides a discussion about the AEEI. They meagerly attempt to justify their selection by explaining that an AEEI of 1.0 concurs with the values assumed in the latest IPCC[4] scenarios and that their assumption follows "the conventional wisdom of energy forecasting whereby the energy/output ratio is expected to decline by 1 per cent a year." [9, p. 83] However, they also concede that the AEEI assumption basically "reflects a state of ignorance."[9, p. 83]

2.1.3 Manne and Richels, Global 2100

Manne and Richels offer the most detailed explanation for their selection of the AEEI parameter. Their model, Global 2100, permits changes in energy demand through two mechanisms: (1) price-induced substitution of non-energy inputs for the energy input, and (2) autonomous energy efficiency improvements (AEEI). The AEEI therefore includes all non-price-effects on the demand for energy. They explain that the sources of these non-price-effects are (1) Government Policy; (2) Structural change (the economic "mix"); and (3) Technical progress[5]. While these sources can also effect

[4]Intergovernmental Panel on Climate Change

[5]No attempt will be made to distinguish between disembodied versus embodied technical progress. For global climate change modeling, the relevant time period is very long and for long time periods the two types of technical progress merge into one.

the relative price of energy,[6] the only aspects relevant to the AEEI are the non-price components. Since the distinction between price and non-price effects is not always clear, the precise value of the AEEI becomes difficult to narrow down. For this reason, Manne and Richels run Global 2100 at several different AEEI settings. Their initial results, published in April 1990, report findings under two assumed values for the AEEI — 0.0 and 1.0 [34]. Later simulations, published in October 1990, report results using four settings for the AEEI — 0.0, 0.5, 1.0, and 1.5 [35].

Manne and Richels explain that the controversy surrounding the AEEI is a result of two distinct viewpoints. They explain that the first viewpoint is held by economists who believe that the AEEI should be set to zero because econometric studies have provided no evidence for autonomous time trends of this type.[7] They explain that the second viewpoint is held by technologically oriented end-use analysts who believe that the AEEI should be set to a value of 1.0 or higher. Manne and Richels' two representations are not entirely correct. While the end-use analysts[8] typically hold a more optimistic belief about AEEI value, economists have not agreed on what the "correct" value of the AEEI should be. Economists generally are waiting for more empirical and theoretical research to be done before they arrive at any conclusions.

2.2 The AEEI: more detailed definitions

This section will take a step back from the details of the models and the model descriptions and will provide a more complete and rigorous definition for the AEEI. Energy efficiency will be defined and the problem of interpreting energy efficiency when output is aggregated will be discussed. Then, the three sources of autonomous energy efficiency improvements suggested by Manne and Richels will be further explained. The Manne and Richels categories provide the broadest definition for the AEEI. The differences which exist among the models can be reconciled through real-

[6]For example, a government policy may design an energy tax. Clearly, the effect of the tax should be included in the price component of energy efficiency improvements.

[7]Manne and Richels cite three studies to support this viewpoint: Brown and Phillips, 1989 [8], Hogan, 1988 [25], and Jorgenson and Wilcoxen, 1989 [29].

[8]See Bodlund et. al. [7], Ross [51], Williams [58], and Williams et. al. [59].

izing that some of the technological progress parameters are defined more narrowly than the Manne-Richels description.

2.2.1 Energy Efficiency and Aggregate Output

Since the AEEI is defined as the rate of autonomous energy efficiency improvements, it would be worthwhile to describe the meaning of "energy efficiency." The energy efficiency of a process is understood to be the ratio of energy output to energy input. While this definition seems rather straightforward, the complexity of the concept becomes apparent when one tries to define energy efficiency for anything other than a simple process. Therefore, energy efficiency is often proxied by energy use per unit economic or physical output. This is called specific energy consumption (SEC) and is a commonly used concept (e.g. miles per gallon in automobiles, etc.).

The SEC can be calculated for a particular product (e.g. energy required to produce a ton of plain carbon steel) or for a specific service (e.g. energy required to produce a thousand lumens). A change over time in these particular SEC measures would indicate a change in energy efficiency, given that the product or service remains the same. We could also calculate the SEC for a collection of goods and services. For example, the SEC for the manufacturing sector could be specified by the ratio of total manufacturing energy use to total value-added in manufactured goods. However, if we are to look at the change in the SEC for the manufacturing sector from one period to the next period, this change may not necessarily represent overall energy efficiency improvements in the manufacturing sector; the underlying composition of manufactured products may change over time. Thus, the interpretation of changes in the SEC becomes unclear when the output is heterogeneous, which occurs whenever the output is aggregated.

Some level of aggregation is required in economic cost models. For this reason, true energy-efficiency improvements should be separated from compositional change effects when considering aggregate ratios of energy use to output. Also, the sources of the true energy-efficiency improvements should be distinguished by price and non-price effects.

2.2.2 Elements of the AEEI

The broadest description of autonomous energy efficiency improvements is described by including all non-price-effects. While this broad definition is relevant to the Manne-Richels Global 2100 model, it does not apply to the Edmonds-Reilly (ERM) or to the OECD GREEN model. Both GREEN and the ERM include the effects of income elasticities (a non-price-effect) on the demand for energy. In addition, GREEN also incorporates the effects of trade on energy demand, another non-price effect. The energy-efficiency description used in these models therefore only includes Manne and Richels third element: technical progress.

Government Policy

Government policies can induce technological progress. For example, average fuel efficiency requirements for automobiles have led to large fuel reductions for the same energy service (transportation). Other programs and laws can bring about similar change. Government activity has been predicted to bring about energy efficiency improvements of over 1.5%.[9] Although public policies may be able to spark initial improvements, they may be unable to sustain long-term efficiency improvements. Indeed, it has been argued that an AEEI of 1.5 is not sustainable over a long period of time [35, p.74]. Given these difficulties, it would be best to leave this factor out of the AEEI parameter, especially since most government policies effect the price (e.g. a tax).

Structural change

All units of GDP are not equal, even though they are measured as if they were equivalent. Some units require more energy in production than others. Thus, an economy can transition into an apparently more "energy-efficient" economy costlessly

[9]Bodlund, Mills, Karlsson, and Johansson [7] estimate that policy initiatives for Sweden, between 1987 and 2010, will improve the efficiency of electricity use on average 1.64% per year. Ross [51] estimates that primary industrial energy demand in the U.S. due to policy changes would decrease by 1.75% annually for 1985-2010. Additionally, Williams believes that government policy is likely to have dramatic effects on future energy use [58].

by changing the composition of its output. Transitions have occurred more rapidly as trade barriers have fallen, creating a more global economy. There is mounting evidence that the industrial countries have reached a point where economic growth is dominated by high-technology products having low materials content. This fact is based on the premise of "materials saturation."[10]

Empirical evidence shows that structural change was responsible for significant reductions in energy use in the manufacturing sector for the U.S., Japan, and West Germany between 1973 and 1988.[11] However, structural change accounted for increases in energy use for the transportation sector[12] and the residential sector[13]. These results show that structural change is indeed significant to energy use trends.

Is structural change sufficiently incorporated into the framework of the general equilibrium model? In Global 2100 it is not, and therefore changes in energy use due to structural change must be included in the AEEI. On the other hand, GREEN includes the effects of structural change through explicit representation of income elasticities and trade patterns. Consequently, the effects of structural change should not be incorporated into the AEEI parameter.

Technical Progress

The third source of non-price-induced energy efficiency growth is technical progress, the phenomenon whereby the aggregate production function shifts with time, resulting in faster output growth than input growth. In other words, when technical progress occurs, the same amount of output can be produced using fewer total inputs.

We can explain this concept within a mathematical framework. The theory was developed by Robert Solow [52]. The basic idea is to include technological change in

[10]See: Williams, Larson, and Ross, 1987 [59].

[11]While increases in sectoral *activity* led to increased manufacturing energy use, the *structural change* within the manufacturing sector contributed to the energy use reductions. The decline in energy-intensive industries within the manufacturing sector lowered manufacturing energy use by 13% in the U.S., 16% in Japan, and 12% in West Germany. [46, p. 194]
See also Bending [4].

[12]Structural change increased energy use in the transportation sector between 1973 and 1988 by 3% in the U.S., 5% in West Germany, and 21% in Japan. [46, p. 194]

[13]Structural change raised energy use in the residential sector by 42% in the U.S., and 60% in West Germany and Japan. [46, p. 194]

the aggregate production function; this allows the production function to shift with time. The total output, Y, is given by the production function

$$Y = f(X_1, X_2, , ..., X_n; A) \tag{2.1}$$

where $X_1, X_2, , ..., X_n$ are the inputs of production and A is the state of technical knowledge. Solow explains that A can be proxied with a variable t for time and represents "slowdowns, speedups, improvements in the education of the labor force, and all sorts of things." [52, p. 312] This allows one to isolate the autonomous element which is often described as "technical progress."

To consider the effects of technical change on energy use, we divide Equation 2.1 by aggregate energy use and specify the dual, assuming cost minimization.

$$Y/E = h(P_1, P_2, ..., P_n; A) \tag{2.2}$$

The equation explicitly shows that the inverse of the energy-GDP ratio depends upon the input prices (P_i) as well as the state of technical knowledge (A). Thus, we see that technical progress can indeed improve energy efficiency autonomously. In practice, it is difficult to separate its effects from the effects of the other variables.

The effects of technical progress on the Energy-GDP ratio, purged of all other effects (the input prices) can be determined by specifying a correct functional form for Equation 2.2, proxying A with t, a variable representing time, and then econometrically estimating the coefficient of time. This estimated coefficient can be considered to be the AEEI. We will estimate this coefficient in Chapter 3 and we will explain the complexities involved in the estimation. Chapter 4 will summarize other empirical studies which have attempted to estimate the effects of technical progress on energy use. We will see that the results of these studies are diverse.

Chapter 3

Econometric Estimation

This chapter presents the methodology and results of a straightforward econometric estimation of the AEEI, when it is considered to be the effects of pure technological change on energy efficiency. The level of aggregation is at the country-level. The model is a single-equation description of the energy-income ratio. The basis for this representation will be explained, the results will be presented, and a discussion of the results concludes the chapter.

3.1 Description of Data Set

A data set containing energy consumption per capita and real GDP per capita was obtained for twenty-three countries over the time period 1951-1990. The countries included eleven advanced economies[1] and twelve LDCs or countries in transition[2]. Real GDP was calculated using purchasing power parities developed by Heston and Summers. A more detailed description of the data set is found in Appendix A.

[1]Australia, Belgium, Canada, Denmark, France, Germany, Italy, Japan, Norway, and Great Britain, and the United States

[2]Brazil, Cameroon, Chile, India, Kenya, Korea, Mexico, Morocco, Nigeria, Philippines, Tunisia, Uganda (*Note: The data for some of these countries covered a shorter interval. Specifically: Chile (1952-1990), Cameroon (1961-1990), Korea (1954-1990), Tunisia (1961-1990), Uganda (1955-1990)*)

3.2 Mathematical Representation of the AEEI

The AEEI can be most clearly understood through a mathematical representation. The AEEI is often understood as the time trend of the energy-GDP ratio. Assuming that the energy-GDP ratio grows exponentially, the ratio can be written as

$$\frac{E}{Y} = \tilde{\alpha} e^{\gamma_1 t} \tag{3.1}$$

where E stands for a country's net consumption of energy, Y is the Gross Domestic Product (GDP) of a country, t is time measured in years, and $\tilde{\alpha}$ and γ_1 are constants to be determined. In this equation, the AEEI is represented by the growth rate of the E/Y ratio, $\left(\frac{\delta(E/Y)}{\delta t} / \frac{E}{Y}\right) = \gamma_1$. This was the representation understood by the GREEN modellers as they justified their choice of the AEEI by reasoning that it should follow the conventional wisdom of energy forecasting whereby E/Y is expected to decline by 1% per year [9, p.83]. For estimation purposes, Equation 3.1 can can be re-written in a linear form,

$$ln \frac{E}{Y} = \alpha_1 + \gamma_1 t. \tag{3.2}$$

3.3 Estimation Procedure

Equation 3.2 can be estimated using ordinary least squares (OLS) regression.[3] However, since we have time series data, it is likely that we have serial correlation which means that one of the assumptions of ordinary least squares regression does not hold. To test for serial correlation, the Durbin-Watson[4] statistic was calculated after OLS estimation was run on Equation 3.2 for each of the twenty-three countries. The Durbin-Watson statistics are shown in Table 3.1. For all twenty-three countries, the Durbin-Watson statistic was less than the lower limit ($d_u = 1.39$), at the 0.05 signifi-

[3]Ordinary least squares is the best linear unbiased estimator if the following assumptions hold: (1) the relationship between the dependent and the independent variables is linear; (2) the independent variables are nonstochastic variables whose values are fixed; and (3) the errors are statistically independent, normally distributed with mean zero, and exhibit constant variance.

[4]For a description of the Durbin-Watson Test, see Pindyck and Ruinfeld, *Econometric Models and Economic Forecasts,* McGraw-Hill, New York: 1991.

Country	DW statistic	Country	DW statistic
Australia	1.19	Brazil	.75
Belgium	.28	Cameroon	.52
Canada	.17	Chile	.56
Denmark	.18	India	.62
France	.29	Kenya	.42
Germany	.43	Korea	.09
Italy	.05	Mexico	.41
Japan	.14	Morocco	.45
Norway	.32	Nigeria	.41
UK	.35	Philippines	.15
United States	.07	Tunisia	.90
		Uganda	.20

Table 3.1: Durbin-Watson statistics obtained after performing OLS on $ln\frac{E}{Y} = \alpha_1 + \gamma_1 t$.

cance level, indicating that positive serial correlation is present. To correct for serial correlation, the Cochrane-Orcutt procedure[5] was used. The Cochrane-Orcutt method assumes that the errors are of the form $\hat{\epsilon}_t = \rho\hat{\epsilon}_{t-1} + v_t$ where $\hat{\epsilon}$ is the residual.[6] The estimation results for Equation 3.2 are reported in Appendix B for all twenty-three countries.

[5]D. Cochrane and G. H. Orcutt, "Application of Least-Squares Regressions to Relationships Containing Autocorrelated Error Terms," *Journal of the American Statistical Association,* 1949, Vol. 44, pp. 32-61.

[6]$\epsilon_i = Y_i - \hat{Y}_i$, where Y_i is the observed value of the dependent variable and $\hat{Y}_i$ is the predicted value of Y_i computed by the ordinary least squares estimation procedure.

3.3.1 Simple Time Trend Analysis: Discussion of Results

The results of Appendix B are summarized in Figures 3-1 and 3-2. The vertical lines in these figures correspond to the confidence intervals of the estimated parameter; the dot on the line corresponds to the estimated value of the coefficient or the constant term.

The estimates for the constant term are shown in Figure 3-1. The constant term is often referred to as the "country term," as it contains all other effects on the energy-GDP ratio except for time. For example, a country in a colder climate is likely to have a higher constant term because more energy is required for heating. This term would also include the industrial structure of a country. The countries with advanced economies have, on average, higher estimates for the constant term than do the LDCs and transitional economies. The average value of the constant term for countries with advanced economies is 10.23; whereas the average value of the constant term for the other countries is 8.44.

The estimates for the coefficient of time are shown in Figure 3-2. This coefficient represents the rate with which the energy-GDP ratio changes over time. Specifically, $\hat{\gamma}_1$ is equivalent to $\frac{\delta e/\delta t}{e}$, where $e = \frac{E}{Y}$. Therefore, $\hat{\gamma}_1$ is the growth rate of the energy-GDP ratio. The figure shows a dramatic difference between the advanced economies and the transitional economies/LDCs. On average, the advanced economies exhibit negative growth rates whereas the other countries exhibit positive growth rates. This observation agrees with the notion that the energy-GDP ratio grows over time with economic development, then levels off, and finally the ratio declines with time as the economy reaches a mature state.[7]

[7]The time trend of the energy-GDP ratio is basically described with an "inverted U" relationship. "Inverted-U" patterns have also been found for various air pollutants and other environmental problems.

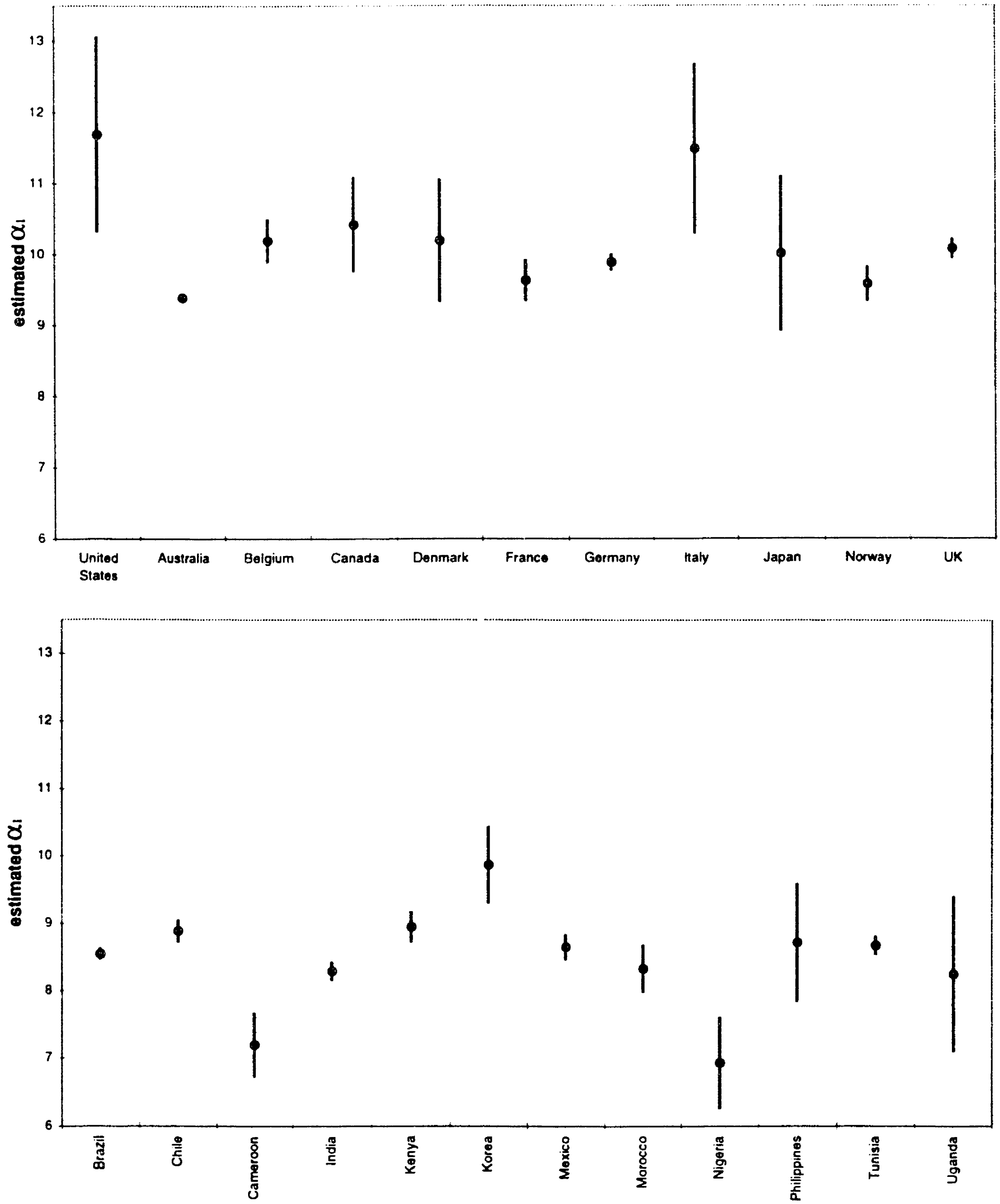


Figure 3-1: Estimated values and confidence intervals for α_1 computed using the model: $\ln(E/Y) = \alpha_1 + \gamma_1 t$. (Results shown from the estimation corrected for serial correlation using the Cochrane-Orcutt procedure.)

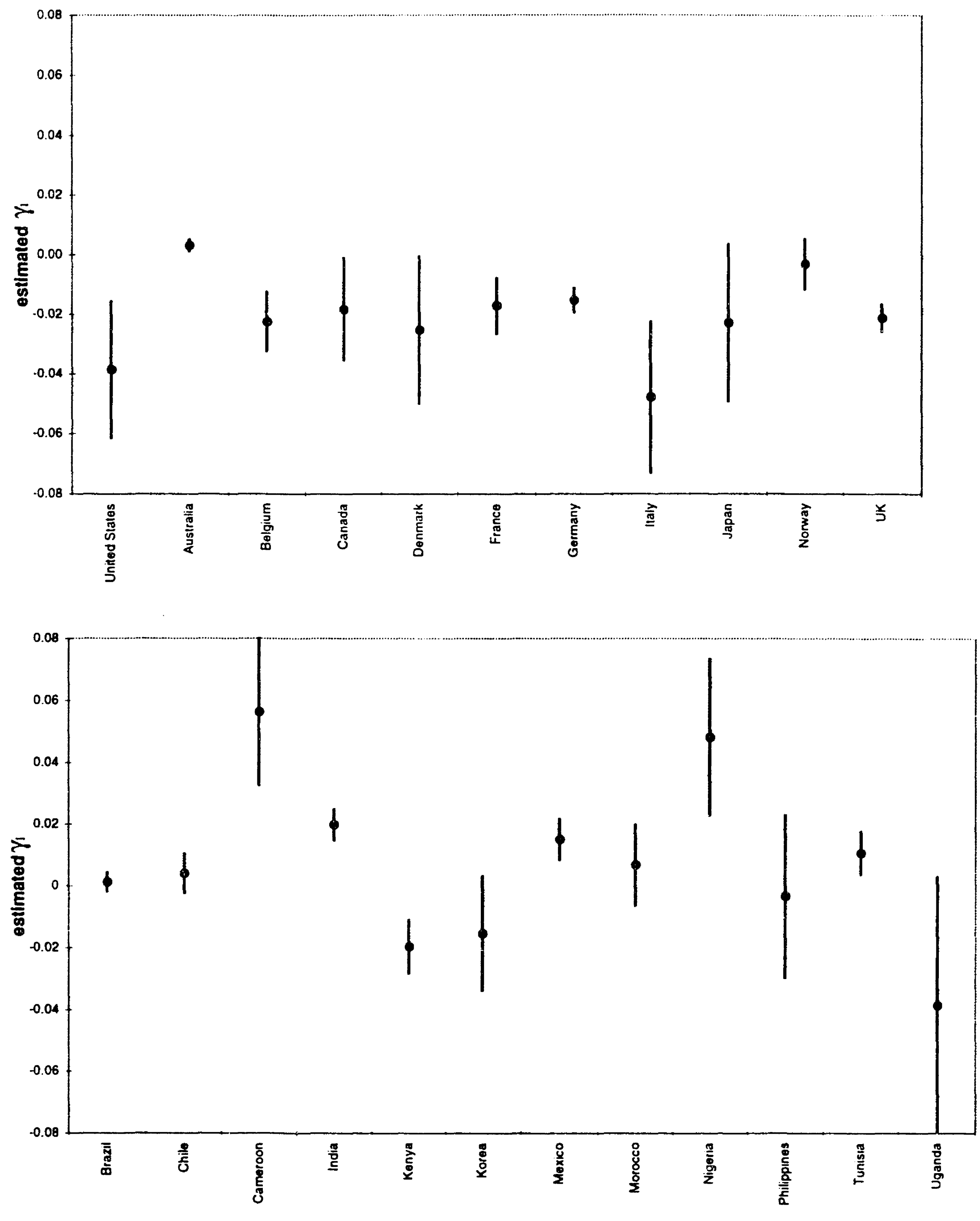


Figure 3-2: Estimated values and confidence intervals for γ_1 computed using the model: $\ln(E/Y) = \alpha_1 + \gamma_1 t$. (Results shown from the estimation corrected for serial correlation using the Cochrane-Orcutt procedure.)

3.4 Decomposing the E/Y Ratio

Certainly, there must be more effecting the AEEI than time effects. The energy-GDP ratio is also likely to be a function of energy price and per-capita income,

$$\frac{E}{Y} = f(y, p, t) \tag{3.3}$$

where y is GDP per capita, p is the price of energy, and t is time measured in years. The E/Y ratio can be assumed to have the functional form,

$$\frac{E}{Y} = \alpha y^{\beta_1} p^{\beta_2} e^{\beta_3 t} \tag{3.4}$$

which can be re-written as,

$$ln\left(\frac{E}{Y}\right) = \alpha' + \beta_1 lny + \beta_2 lnp + \beta_3 t \tag{3.5}$$

Equation 3.5 can be estimated using linear regression techniques after we re-write the equation by grouping the common term, Y.[8] Our equation is now written with energy use per capita as the dependent variable instead of our familiar E/Y ratio as the dependent variable.

$$ln(E/capita) = \alpha' + (\beta_1 + 1)lny + \beta_2 lnp + \beta_3 t \tag{3.6}$$

This equation can be estimated using the data if changes in price are assumed to be negligible. Results estimated by OLS and OLS corrected for serial correlation are reported in Appendix C. All results were reported using the notation in Equation 3.5. The regression results were simply adjusted. The statistics package calculates the estimated coefficient $(\beta_1 + 1)$ and reports the t-statistic which tests if $\beta_1 + 1 = 0$. However, the coefficient β_1 and the t-statistic which tests if $\beta_1 = 0$ are reported in Appendix C and Figure 3-4.

[8]We have GDP (Y) on both sides of our equation. Recall that $y = Y/capita$

3.4.1 Effects of time and per-capita income on E/Y ratio: Discussion of Results

The results of Appendix C are summarized in Figures 3-3, 3-4, and 3-5. These figures contain the estimates and confidence intervals for α', β_1, and β_3. The vertical lines in the figures correspond to the confidence intervals of the estimated parameter; the dot on the line corresponds to the estimated value of the parameter.

Figure 3-3 shows the estimates for the country term (α'). The two country groups exhibit similar ranges for the estimated value. The constant term ranges, on average, between five and fifteen. These estimates contrast with the previous estimates of the country term in the model that did not contain per-capita GDP (compare Figure 3-3 with Figure 3-1).

Figure 3-4 shows the estimates for the coefficient of per-capita GDP, $\hat{\beta}_1$. Rather dramatic differences exist between the country groups. On average, the advanced economies exhibit positive values for $\hat{\beta}_1$, whereas the lesser developed countries exhibit slightly negative values for $\hat{\beta}_1$.

Figure 3-5 reports the estimated values and confidence intervals for the coefficient of time. As was discussed in Section 3.3.1, this coefficient corresponds to the pure time effects on the growth rate of the Energy-GDP ratio.[9] Again, we see a dramatic difference between the two country groups. On average, the Advanced Economies exhibit negative values for the time coefficient, whereas the Lesser Developed Countries exhibit positive values for the time coefficient. These results suggest that the AEEI, as represented by pure time effects, should vary with the country's stage of economic development.

[9] Assuming that the model is correct. The most obvious problem with the model is the omission of a price term for energy. We are assuming that price changes are negligible. As we will see in the next section, this is a reasonable assumption.

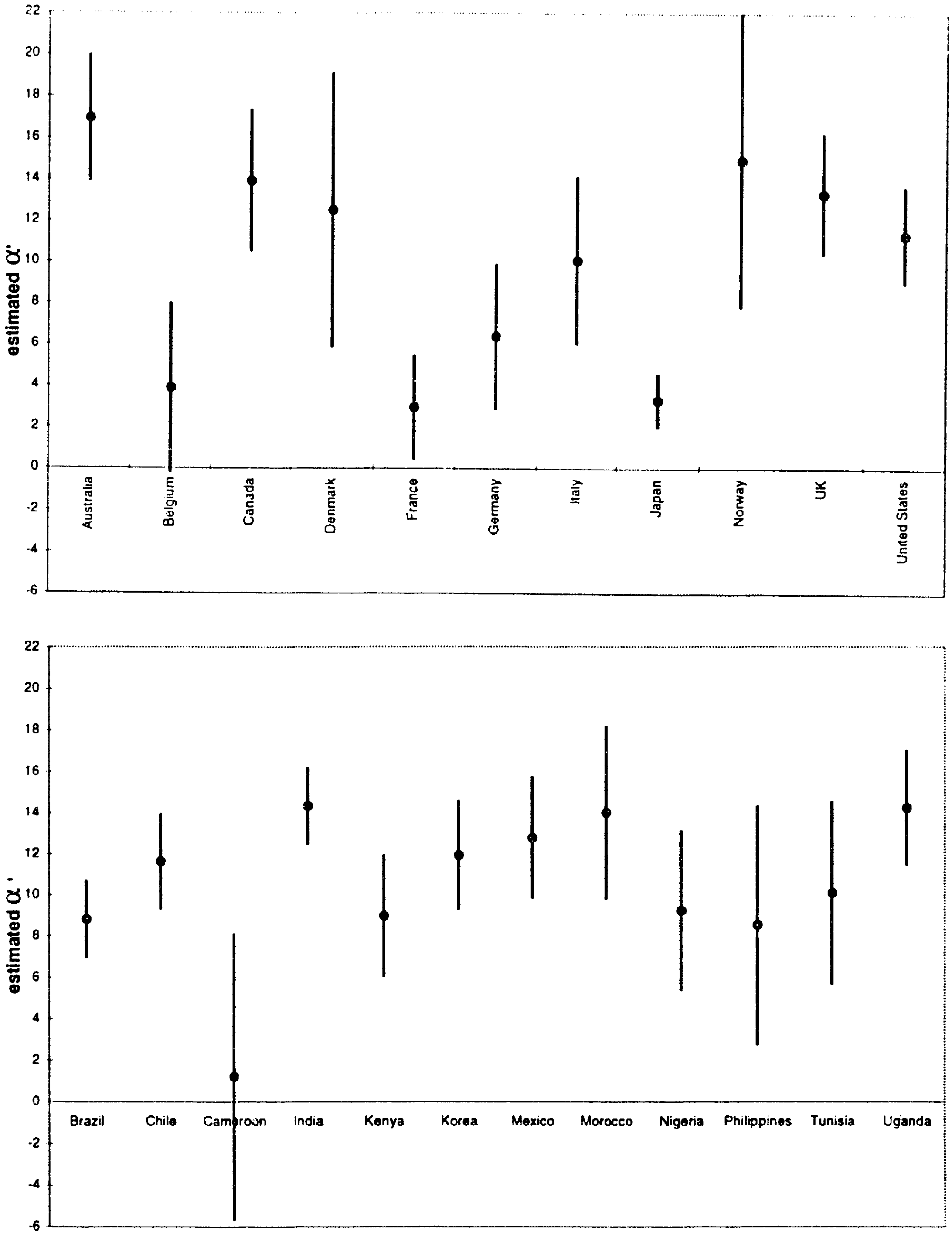
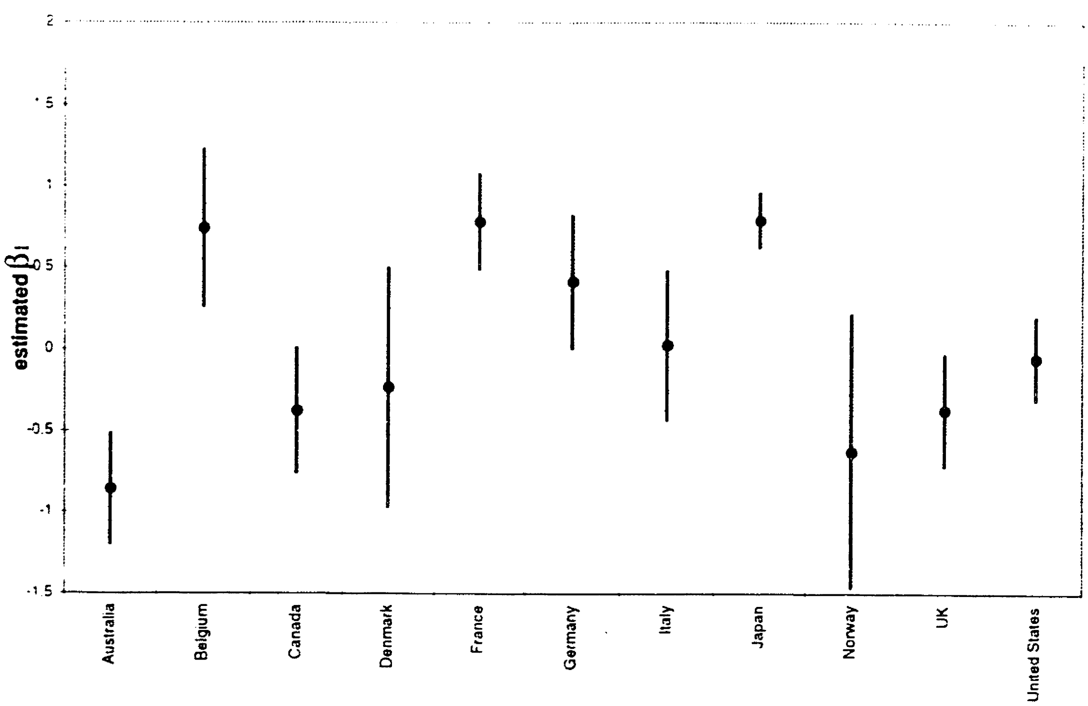


Figure 3-3: Estimated values and confidence intervals for α' computed using the model: $ln(\frac{E}{Y}) = \alpha' + \beta_1 lny + \beta_2 lnp + \beta_3 t$. (Results shown from the estimation corrected for serial correlation using the Cochrane-Orcutt procedure.)



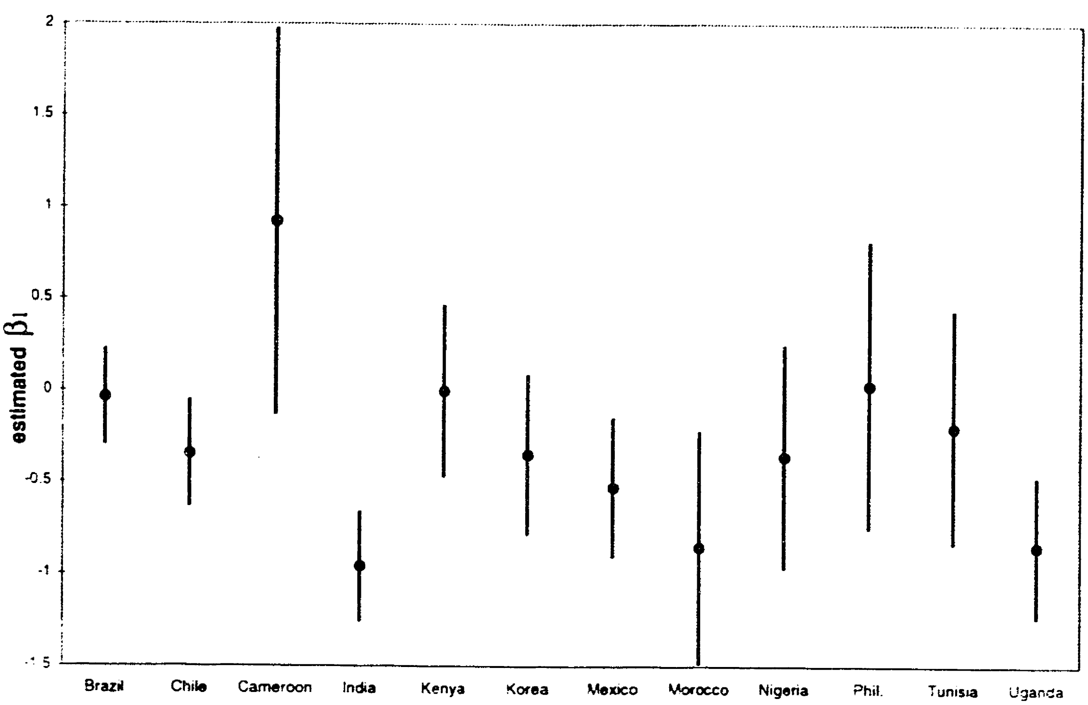
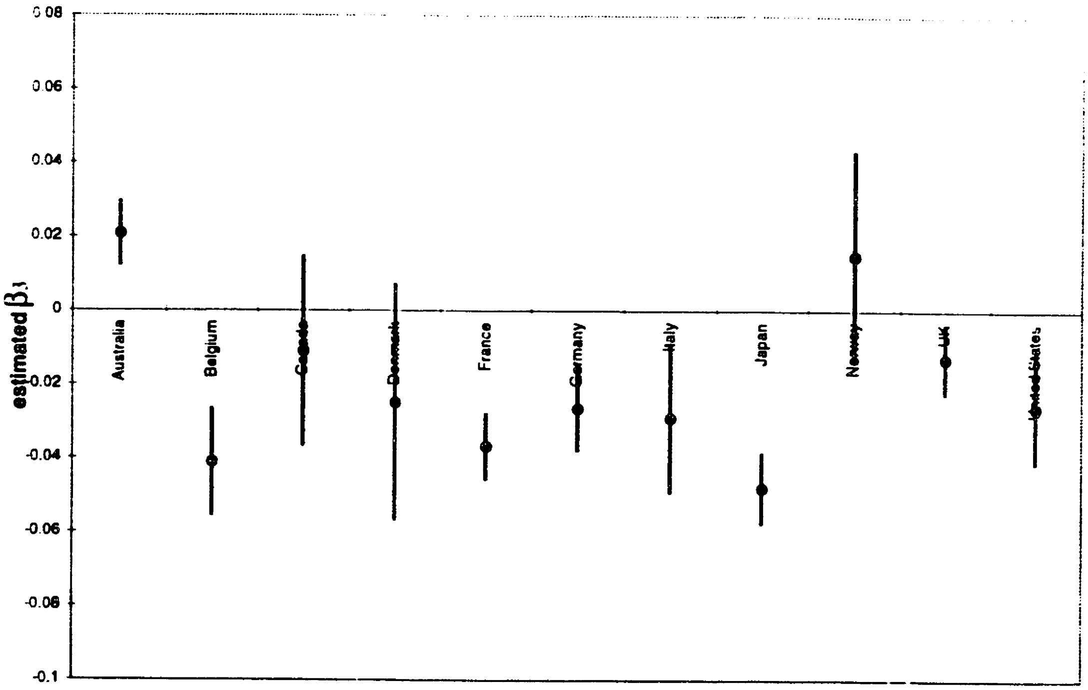


Figure 3-4: Estimated values and confidence intervals for β_1 computed using the model: $ln(\frac{E}{Y}) = \alpha' + \beta_1 lny + \beta_2 lnp + \beta_3 t$. (Results shown from the estimation corrected for serial correlation using the Cochrane-Orcutt procedure.)



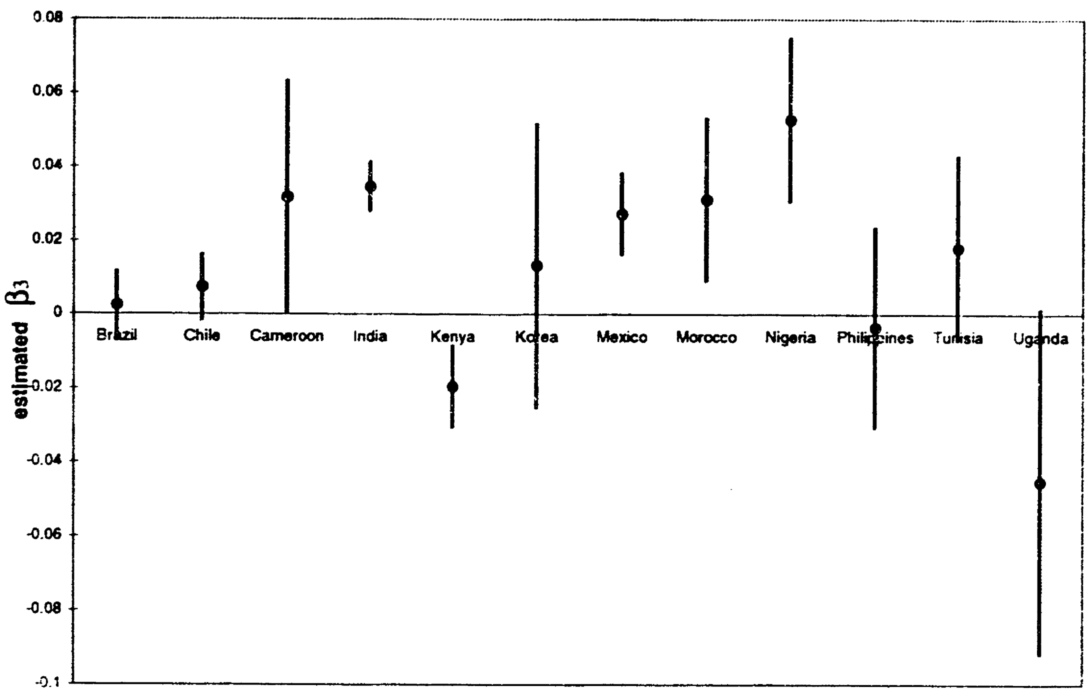


Figure 3-5: Estimated values and confidence intervals for β_3 computed using the model: $ln(\frac{E}{Y}) = \alpha' + \beta_1 lny + \beta_2 lnp + \beta_3 t$. (Results shown from the estimation corrected for serial correlation using the Cochrane-Orcutt procedure.)

$\ln(E/Y) =$	α'	$+\beta_1 lny$	$+\beta_2 lnp$	$+\beta_3 t$	ρ	Adj. R^2
Time only	11.69			-.0390	.975	.22
	(17.41)			(3.43)	(328)	
GDP per capita added	11.33	-.059		-.0262	.958	.60
	(9.97)	(.48)		(3.57)	(118)	
Price term added						
Composite Fossil Fuel Price	11.96	-.109	-.033	-.0253	.961	.60
	(9.72)	(.84)	(1.17)	(3.20)	(130)	
CPI-U	12.56	-.216	-.084	-.0269	.932	.58
	(8.70)	(1.41)	(1.23)	(4.21)	(78)	

Table 3.2: Results of performing linear regression (corrected for serial correlation) on data for the United States, 1951-1990. The estimated coefficients, along with the absolute value of the t-statistic are shown along with ρ and R^2. Four specifications were used, all having ln(E/Y) as the dependent variable. The first specification includes time as the only explanatory variable. The next specification includes per-capita GDP along with time. The last two specifications also include a price term.

3.4.2 Inclusion of price into the model for the U.S.

This section will discuss estimation results when a price term is included in the regression equation. The estimates were determined for the United States. Two aggregate measures of the energy price were used. First, the Consumer Price Index[10] for the energy group was used.[11] Second, a composite[12] fossil fuel real price was used.[13] Both of these measures of energy price were indexed to a certain year and reported in constant dollars.

Equation 3.5 was estimated using OLS corrected for serial correlation by using the Cochrane-Orcutt procedure. The results of the estimation are shown in Table 3.2. The table also includes the estimates from the specifications which do not include a price term. Time clearly emerges as an important explanatory variable regardless

[10]Specifically, the CPI-U – Consumer Price Index for Urban areas – was used.

[11]Source: Bureau of Labor Statistics, *Monthly Labor Review*, and *Handbook of Labor Statistics*.

[12]The composite value was derived by summing over price (per Btu) multiplied by total quantity produced (in Btus) for each fossil fuel. Then, this summation was divided by the accumulated Btu content of total fossil fuel production.

[13]Source: *Annual Energy Review 1990*, U.S. Energy Information Administration

of model specification. Somewhat surprisingly, the coefficient on price is insignificant for both models which include price.

3.5 Recommendations for additional econometric analysis

Much more econometric analysis can be performed on this data. Suggestions for alternative specifications are listed below.

- Develop a model with a lagged dependent variable ($\frac{E}{Y}_{t-1}$ or $\ln(E/Y)_{t-1}$). Serial correlation can be corrected using an instrumental variables procedure with a grid search.
- Consider a simultaneous-equation estimation where Energy=f(price per-capita GDP, time) and Per-Capita GDP = g(energy price, energy use, time).
- Group the data from several countries together and use the F-test to determine whether this pooling is valid.

Chapter 4

A Survey of Results from other Empirical Studies

The analysis of Chapter 3 provided us with insight into the energy-GDP relationship across countries. Some general assessments regarding differences between the developed countries and the countries in transition were made. In addition, the composite price of energy was shown for the U.S. to have negligible effects on the changing energy-GDP ratio over time. Admittedly, the econometric analysis was rather unsophisticated, but it provides a benchmark for comparison with other studies and it provides a quantitative framework with which to describe the Energy-GDP ratio. This chapter will consider other studies which have attempted to quantitatively understand the energy-GDP relationship. Energy-economic analysts have come to different conclusions regarding the factors which influence the energy-GDP ratio. This chapter will explain why these differences exist, how they help us to understand the AEEI, and how these studies compare with the analysis of Chapter 3.

4.1 Introduction

A plethora of information exists which examines the relationship between energy demand and overall economic activity. The studies which may illuminate our understanding of the AEEI can be grouped into two categories: (1) sectoral analyses, and

(2) studies of demand elasticities. These studies attempt to decompose growth (negative or positive) of the E/Y ratio into various components. The component which is relevant to the AEEI is the effect of the pure time trend, which is also referred to as 'technical progress.' The literature was examined to determine the conclusions that have been reached regarding the effects of the pure time trend on the E/Y ratio. Surprisingly, few solid conclusions regarding technical change and the E/Y ratio could be gleaned from these empirical studies.

4.2 Sectoral Analyses

Sectoral analyses[1] attempt to disaggregate the Energy-GDP ratio into various components (e.g. transport, industry, residential, commercial). In addition, these studies then take the disaggregated sectoral Energy/GDP ratio and separate the effects of structural differences from energy intensity differences. Structural differences include such factors as the size of the industrial sector, the differences in the product mix, the vintage of energy-using capital stocks, climate, population density, propensity to travel, policies affecting use of energy, and life-style attributes. Energy-intensity, on the other hand, refers to the amount of energy used in producing reasonably homogeneous goods or services. Thus, the purpose of these types of studies is evaluation of inter-country differences in economic structure and energy-intensity. Where there were differences in the intensity, it was thought that there was potential for energy conservation.

In addition, some of these studies attempt to track time-trends of energy use among the various sectors of an economy. Basically, this can be understood through a mathematical representation similar to the format presented in Chapter 3. But, instead of decomposing the E/Y ratio into time effects and income effects, the ratio is decomposed into energy intensity changes and structural change effects. Letting t proxy the state of technical knowledge and letting S represent the structure of the economy, where a higher value of S indicates an economic mix which physically

[1]Such studies include [45], [12], [27], [57], [44], [4], [38], [37] and [14].

requires more energy in production, we can write

$$E/Y = ae^{\beta_1 t}e^{\beta_2 S} \tag{4.1}$$

$$\ln(E/Y) = \alpha + \beta_1 t + \beta_2 S \tag{4.2}$$

Note that the changes in energy intensity can be represented by the coefficient on t *if* it is assumed that changes in the energy price are negligible. Although not presented with this mathematical representation, Lee and Schipper in [46] decompose the changes in the E/Y ratio into structural and energy intensity components. They report that aggregate changes in the E/Y ratio for the industrialized countries can be attributed in large part to the declining energy intensities within the sectors.[2] This analysis suggests that the AEEI is indeed an important component of changes in the E/Y ratio. However, sectoral analyses must be looked at critically because the method by which structural change is quantified can be somewhat subjective. Also, sectoral analyses generally are descriptive and do not provide explanation for the causation of the changes. For the purpose of this thesis, the drivers of the energy intensity changes are of interest. Is technical change purely responsible for energy intensity changes over time? Or, are price effects and government policies also effecting the change in energy intensity?

4.3 Estimation of Income and Price Elasticities

Econometric methods offer a more quantitative treatment of decomposing the growth of the E/Y ratio. Also, the causal relationship is explicitly defined in an econometric model. Thus, studies which econometrically estimate elasticities of energy demand are likely to offer a quantitative description of the effect of the time trend on energy demand. In general, the purpose of these studies was to predict energy demand, to estimate the effects of price and income on fuel demand, and to explore substitution

[2]They found that declining energy intensities account for 75% and 50% of the decrease in the E/GDP ratio for the United States and Japan, respectively. [46, p. 62]

possibilities between fuel types.[3] The effect of technological progress on energy demand was only included as a means of providing more precision to the income and price elasticity estimates. Thus, in order to understand what the studies have to say about the AEEI, one must wade deeply into the methodology of the papers to understand how technical change effects were included, and if included, to interpret the results reported in the studies.

Unfortunately, a review of the literature shows that most of the studies are not of much help in clarifying the AEEI parameter for three reasons. First, most of the studies are relatively short-term.[4] On average, they cover about ten years. Second, most of the studies simply ignore the effects of technological change on energy demand. The second reason is probably closely related to the first reason because the effects of technical progress may be different, and may possibly be negligible, over shorter time periods. Lastly, since the purpose of the studies was to estimate elasticities and not to measure the effects of technical change on energy demand, the effects of technical change may have been glossed over and may have been prematurely considered insignificant.

4.4 Studies which include Technical Change

Although most of the studies reviewed did not include a time term in their econometric model, three of the reviewed studies include this term. These studies will be reviewed here in more detail. The methodology and results will be presented and their relevance to the AEEI will be explained.

[3]Attention was focused on energy demand due to the mounting concern of reduced energy supply. There were many advocates of energy conservation during the 1970s and early 80s, and many studies were performed to evaluate the soundness of energy conservation programs. There was concern that energy conservation would lead to a lower standard of living and real welfare losses.

[4]We are considering the studies which attempt to estimate short- and long-term estimates of various parameters. Even though these studies include long-term price and income elasticity estimates, the period considered is short relative to time periods relevant for global climate change.

4.4.1 Real Price and the Consumption of Mineral Energy in the U.S., 1901-1968

The purpose of this study by Edmonson [19] was to determine whether there is a measurable historical relation between price and total fossil energy consumption. As expected, he finds that there is indeed a measurable relation between price and energy consumption. The initial specification used by Edmonson consists of aggregate supply and demand equations for fossil energy.

$$\begin{aligned} \text{DEMAND}: \quad ln(E/N) &= \alpha_0 + \beta_1 ln(X/N) + \beta_2 lnP + \beta_3 lnR \\ &+\alpha_1 d_1 + \alpha_2 d_2 + \alpha_3 d_3 + \alpha_4 d_4 \\ &+\gamma_1 ln(X/N)_{-1} + \gamma_2 lnP_{-1} \qquad (4.3) \\ \text{SUPPLY}: \quad lnE &= Z + B_1 lnP + B_2 d_4 + B_3 d_5 \\ &+b_1 t_1 + b_2 t_2 + b_3 t_3 + b_4 t_4 + b_5 t_5 \qquad (4.4) \end{aligned}$$

where E is apparent consumption of mineral fuels in BTUs, X is real GNP, N is the total population of the U.S., P is the nominal price level of energy[5], R is the real price of energy-consuming goods[6], d_1 through d_5 are dummy variables for specific periods[7], and t_1 through t_5 are dummies covering five time segments[8]. He then uses the two-stage least squares procedure to estimate the coefficients and intercepts using U.S. data from 1901-1968. As in the OECD study [23], the time variables used in this study also represent technical progress in the *production* of energy. The time variables, $t_1 ... t_5$ are used to represent the effect of "autonomous forces in the supply relationship." He further explains, "These have consisted of technological changes

[5]The energy price was based on average unit prices for anthracite and bituminous coal, crude petroleum, natural gas, and natural gas liquids. A linked Laspeyres price index was developed using consumption weights. The real price of energy was derived by deflating the nominal price with the wholesale price index.

[6]$R = q(r + \delta - q)/w$, where q is the purchase price of the energy-consuming good, r is a long-term rate of discount, δ is the depreciation rate, $\dot{q}$ is the time rate of change of q, and w is the price level of goods in general.

[7]d_1, d_2, d_3, d_4, and d_5 correspond to 1901-15, 1916-29, 1942-1946, 1918, and 1919-1922 respectively.

[8]The five time segments are 190110, 1911-20, 1921-31, 1932-50, 1951-68.

of many kinds, discoveries of major fuels deposits, wars, and other events for which no adequate continuous variable exists." [19, p. 165]. The estimated coefficients for these time variables were *positive,* contrasting with the time coefficients that we understand to be a result of technical progress related to the AEEI. Therefore, just because a model includes a time term which is used to represent technical progress, the estimated coefficient on this time variable may not necessarily represent energy efficiency improvements as described by the AEEI.

The difference between the effects of technical change on the production and consumption of energy are realized in Edmonson's final specification, which includes a third equation in the model. He acknowledges that energy may also be considered to be a dependent variable effecting the level of aggregate output, which therefore requires a third equation to enter the model.

$$lnX = a_0 + k_1 lnE + k_2 lnL + k_3 O/HP \tag{4.5}$$

This third equation[9] incorporates the effects of technical change on energy *use* by including a variable which describes the efficiency of energy use in the production of goods and services. This variable is represented by O/HP, the ratio of output[10] to installed electric motor horsepower in manufacturing establishments.[11] The estimated coefficient of this variable is positive, corresponding to a negative coefficient in the framework of Chapter 3.[12]

4.4.2 An Econometric Analysis of U.S. Oil Demand

This study by Brown and Phillips [8] examines a single fuel type, oil. Although the focus of this thesis is on aggregate energy consumption, it is important to discuss this

[9] In this equation, L is the employed labor force.

[10] The output measure is the FRB industrial production index for manufacturing.

[11] He uses this ratio under the assumption that "the state of the art of using electrical energy in manufacturing has reflected the state of the art of using energy in production for the economy as a whole during the study period."[19, p. 171]

[12] Edmonson's equation has aggregate output as the dependent variable, whereas the analysis of this thesis has energy as the dependent variable.

study because it reveals the misunderstanding associated with autonomous efficiency improvements in energy use.

The model used in this study explicitly incorporates the effects of technological change on U.S. oil demand by including a time-counter variable. U.S. oil consumption was modeled as a function of past and present real prices of crude oil, real gross national product, and the share of GNP in the industrial sector.[13] They found the coefficient of the time term to be statistically insignificant, and they conclude that non-price conservation[14] is not supported by empirical evidence. It seems reasonable to believe that the effects of technological change do not appear in their results due to the relatively short time period (1972-1988) and due to the fact that they were only considering one fuel type.

4.4.3 Energy consumption and economic activity in industrialized countries

This econometric study is the most relevant for the purposes of estimating non-price-induced energy efficiency improvements. The reasons for this are the long time-period (1950-1978), the aggregate nature of the study (the entire economy is considered), and the inclusion of a time term. They explain the importance of including a time term by explaining,

> "$\delta_1 t$ is a time trend that proxies secular movements in energy productivity. Proxying technical progress in this way is never very satisfactory although it is common practice. On the other hand to ignore technical progress for want of a superior representation would, in our opinion, amount to model misspecification since there can surely be little doubt about the existence of technical progress in energy usage. Indeed, to ignore it would tend to induce downward bias in [the estimated] elasticities."

[13]They used natural logs of all the variables and modeled the effects of price as a ninth-degree polynomial distributed lag.

[14]They describe non-price conservation as the event where changes in government policy and technology have reduced U.S. oil demand independently of the influence of price.

They used a dynamic estimation technique[15] to estimate a steady-state equation,

$$lnE = 1.0149 + 1.777lnQ - 0.0551lnP - 0.0357t \tag{4.6}$$

The coefficient on the time term was significant, having a t-statistic of 4.29. In addition, the time term was dropped to assess its significance. It was found that dropping the time term adversely affected the statistical properties of the model.

4.5 Interpreting the studies within the context of the global warming problem

The review of the empirical literature provides little to guide selection of the AEEI. The three studies which do include the effects of technical change suggest negative values for the AEEI, as expected for the developed economies. However, these studies have rather severe shortcomings. Specifically, the Brown and Phillips study only considers oil demand, and only over a short period (1972-1988). The other two studies estimate over longer periods and consider aggregate energy use, but their period of estimation closes from 17 to 27 years ago. Therefore, econometric analysis of the AEEI parameter should be encouraged in order to guide its selection.

[15] The dynamic procedure they used is called the 'error correction' methodology developed by Mizon and Hendry[40].

Chapter 5

Conclusions

- The E/Y ratio should not be used as an indicator of "energy efficiency." This aggregate ratio overstates the true value of energy efficiency improvements because it also includes price, income, and other structural effects.

- While the AEEI dramatically affects estimates of future CO_2 emissions in the cost models, there is very little in the empirical literature to guide selection of the AEEI. Furthermore, the empirical studies which include technical change in the econometric specification are dated or consider a short time period.

- The straightforward econometric estimation techniques used in this thesis and related past studies strongly suggest that the AEEI is important, as indicated by the statistically significant coefficient of the time term. These studies also agree that the AEEI should take on a negative value.

- The term "AEEI" has been carelessly used to describe many different energy efficiency parameters of various models. The parameter name, AEEI, has only been used explicitly in the Manne and Richels model. Caution should be exercised when using Manne and Richel's definition of the AEEI in other models because double-counting may result. The only common element among the parameters of the various models is that they all describe phenomena which are not directly specified in the models.

Appendix A

Documentation of Data Set

The data[1] used in the analysis for each of the 23 countries are defined as:

LPCGDP = log per-capita real GDP, in 1985 Purchasing Power Parity dollars, as calculated by Heston-Summers (Penn World Table).[2]

LPCBTU = log of BTUs[3] consumed per thousand people.

[1]The data was developed by Richard Schmalensee, Thomas M. Stoker, and Ruth A. Judson. They graciously permitted the data to be used in this thesis.

[3]Net apparent consumption of energy. This data was acquired from the United Nations.

Appendix B

Simple Model Estimation Results

Model: $ln\frac{E}{Y} = \alpha_1 + \gamma_1 t$

(estimation method: OLS)

Country	$\hat{\alpha}_1$ (t-statistic)	$\hat{\gamma}_1$ (t-statistic)	R-square
United States	10.16	-.012	.761
	(414)	(-11.01)	
Australia	9.38	.003	.410
	(677)	(5.15)	
Belgium	10.10	-.018	.882
	(407)	(-16.83)	
Canada	10.07	-.008	.537
	(387)	(-6.64)	
Denmark	9.49	-.003	.055
	(200)	(-1.48)	
France	9.54	-.013	.840
	(447)	(-14.13)	
Germany	9.91	-.016	.928
	(605)	(-22.05)	
Italy	8.73	.012	.367
	(156)	(4.69)	
Japan	9.28	-.113	.099
	(244)	(-2.05)	
Norway	9.47	.001	.018
	(354)	(0.83)	
UK	10.02	-.019	.961
	(712)	(-30.39)	

Model: $ln\frac{E}{Y} = \alpha_1 + \gamma_1 t$ (estimation method: OLS)

Country	$\hat{\alpha_1}$ (t-statistic)	$\hat{\gamma_1}$ (t-statistic)	R-square
Brazil	8.50	.0024	.171
	(447)	(2.80)	
Cameroon	7.28	.0536	.838
	(97)	(12.05)	
Chile	8.90	.0030	.148
	(342)	(2.53)	
India	8.26	.021	.927
	(378)	(22.03)	
Kenya	8.77	-.0133	.506
	(182)	(-6.24)	
Korea	8.63	.0253	.601
	(118)	(7.26)	
Mexico	8.69	.013	.785
	(336)	(11.78)	
Morocco	8.39	.0042	.087
	(166)	(1.90)	
Nigeria	7.01	.045	.764
	(77)	(11.10)	
Philippines	8.14	.0145	.423
	(131)	(5.28)	
Tunisia	8.61	.0142	.322
	(248)	(6.88)	
Uganda	7.29	-.003	.009
	(65)	(-.55)	

Model: $ln\frac{E}{Y} = \alpha_1 + \gamma_1 t$

(Corrected for serial correlation using Cochrane-Orcutt Procedure)

Country	$\hat{\alpha}_0$ (t-statistic)	$\hat{\gamma}$ (t-statistic)	$\hat{\rho}$ (t-statistic)	R-square
United States	11.69	-.0390	.975	.2409
	(17.41)	(-3.427)	(328.34)	
Australia	9.39	.0030	.398	0.2013
	(410.39)	(3.054)	(2.70)	
Belgium	10.20	-.0225	.881	0.3643
	(70.34)	(-4.604)	(12.81)	
Canada	10.42	-.0184	.944	0.1144
	(32.36)	(-2.187)	(37.09)	
Denmark	10.20	-.0254	.928	0.1057
	(24.29)	(-2.091)	(38.40)	
France	9.63	-.0173	.888	0.2782
	(69.94)	(-3.776)	(12.87)	
Germany	9.89	-.0155	.769	0.6168
	(189.65)	(-7.718)	(8.04)	
Italy	11.48	-.0479	.963	0.2871
	(19.66)	(-3.86)	(329.16)	
Japan	10.01	-.0231	.952	0.0790
	(18.76)	(-1.781)	(58.87)	
Norway	9.58	-.0034	.839	0.0183
	(84.03)	(-.831)	(11.65)	
UK	10.08	-.0214	.838	0.7115
	(163.10)	(-9.55)	(11.37)	

Model: $ln\frac{E}{Y} = \alpha_1 + \gamma_1 t$ (Cochrane-Orcutt Procedure used)

Country	$\hat{\alpha_0}$ (t-statistic)	$\hat{\gamma}$ (t-statistic)	$\hat{\rho}$ (t-statistic)	R-square
Brazil	8.54	.0011	.563	0.0143
	(236.98)	(.734)	(4.873)	
Cameroon	7.19	.0563	.726	0.4676
	(31.88)	(4.869)	(5.922)	
Chile	8.88	.0040	.722	0.0430
	(115.69)	(1.271)	(6.345)	
India	8.29	.0197	.701	0.6344
	(134.55)	(8.013)	(6.043)	
Kenya	8.95	-.0197	.705	0.3658
	(83.94)	(-4.62)	(8.939)	
Korea	9.87	-.0154	.912	0.0785
	(35.75)	(-1.702)	(78.401)	
Mexico	8.65	.0149	.783	0.3563
	(100.06)	(4.526)	(8.446)	
Morocco	8.33	.0067	.773	0.0279
	(49.55)	(1.031)	(7.739)	
Nigeria	6.93	.0481	0.793	0.2866
	(21.09)	(3.856)	(8.139)	
Philippines	8.72	-.0035	.918	0.0019
	(20.34)	(-.266)	(28.054)	
Tunisia	8.67	.0106	.491	0.2656
	(141.47)	(3.125)	(3.486)	
Uganda	8.25	-.039	.884	0.0981
	(14.72)	(-1.894)	(22.691)	

Appendix C

Decomposition Model Estimation Results

Model: $ln\frac{E}{Y} = \alpha' + \beta_1 lny + \beta_3 t$

(estimation method: OLS)

Country	$\hat{\alpha}'$ (t-statistic)	$\hat{\beta}_1$ (t-statistic)	$\hat{\beta}_3$ (t-statistic)	R-square
United States	3.48	.736	-.0264	.6861
	(1.158)	(2.218)	(-4.012)	
Australia	11.22	-.208	.0077	0.9794
	(8.283)	(-1.354)	(2.248)	
Belgium	1.03	1.076	-.0498	0.9289
	(.898)	(7.905)	(-12.369)	
Canada	9.26	0.09	-.0103	0.8961
	(3.741)	(.328)	(-1.277)	
Denmark	-6.74	1.89	-.0532	0.9374
	(-3.646)	(8.782)	(-9.123)	
France	3.47	0.72	-.0352	0.9760
	(5.161)	(9.045)	(-14.208)	
Germany	9.55	0.04	-.0173	0.9358
	(11.558)	(.442)	(-5.549)	
Italy	-9.02	2.19	-.0695	0.9892
	(-7.931)	(15.608)	(-13.181)	
Japan	3.35	0.78	-.0482	0.9961
	(9.123)	(16.183)	(-17.031)	
Norway	11.26	-.21	.0082	0.9580
	(3.086)	(-.491)	(.556)	
UK	11.90	-.22	-.0139	0.5243
	(5.253)	(-.833)	(-2.344)	

$ln\frac{E}{Y} = \alpha' + \beta_1 lny + \beta_3 t$ (estimation method: OLS)

Country	$\hat{\alpha}'$ (t-statistic)	$\hat{\beta}_1$ (t-statistic)	$\hat{\beta}_3$ (t-statistic)	R-square
Brazil	8.17	0.047	.0007	0.9822
	(12.45)	(.510)	(.221)	
Cameroon	-4.01	1.730	.0064	0.9575
	(-1.60)	(4.491)	(.579)	
Chile	8.87	0.004	.0029	0.7996
	(7.91)	(.030)	(1.74)	
India	12.75	-.714	.0315	0.9845
	(15.19)	(-5.348)	(15.368)	
Kenya	9.82	-.165	-.0113	0.1686
	(4.92)	(-.526)	(-2.637)	
Korea	19.07	-1.610	.1237	0.9805
	(14.45)	(-7.913)	(9.808)	
Mexico	11.76	-.396	.0234	0.9736
	(10.45)	(-2.727)	(6.145)	
Morocco	12.06	-.555	.0200	0.8612
	(5.97)	(-1.815)	(2.233)	
Nigeria	11.37	-.703	.0587	0.9024
	(9.60)	(-3.691)	(11.448)	
Philippines	-.428	1.254	-.0098	0.8864
	(-.22)	(4.403)	(-1.65)	
Tunisia	9.54	-.133	.0192	0.9595
	(6.03)	(-.589)	(2.174)	
Uganda	6.17	0.170	-.0027	0.2145
	(2.30)	(.418)	(-.477)	

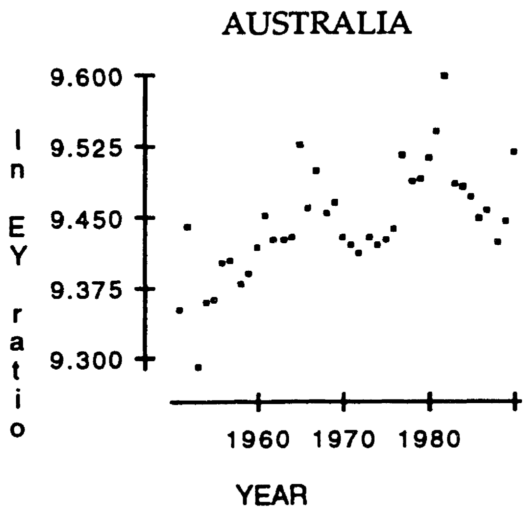
(Corrected for serial correlation using Cochrane-Orcutt Procedure)

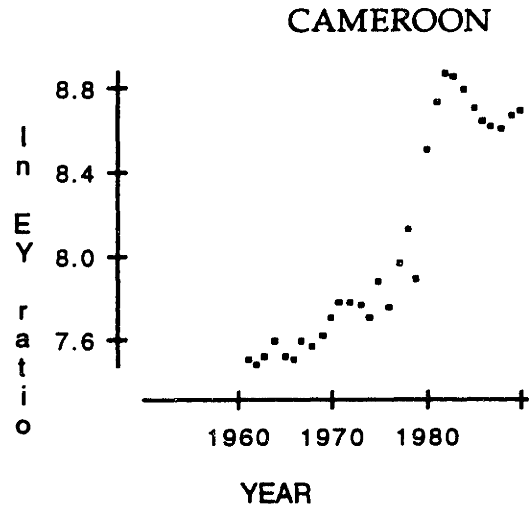
Country	$\hat{\alpha}'$ (t-statistic)	$\hat{\beta}_1$ (t-statistic)	$\hat{\beta}_3$ (t-statistic)	$\hat{\rho}$ (t-statistic)	R-square
United States	11.33	-.059	-.0262	.958	.6202
	(9.972)	(-.479)	(-3.573)	(118.45)	
Australia	16.95	-.858	.0208	.786	0.7512
	(11.488)	(-5.125)	(4.951)	(7.902)	
Belgium	3.88	0.741	-.0412	.697	0.6843
	(1.937)	(3.114)	(-5.792)	(6.049)	
Canada	13.91	-.380	-.01112	.960	0.2421
	(8.325)	(-2.036)	(-.887)	(60.413)	
Denmark	12.50	-.239	-.0250	.938	0.1236
	(3.846)	(-.661)	(-1.596)	(52.921)	
France	2.94	0.779	-.0368	.605	0.9024
	(2.398)	(5.399)	(-8.473)	(4.819)	
Germany	6.37	0.411	-.0265	.721	0.7308
	(3.714)	(2.054)	(-4.756)	(10.371)	
Italy	10.07	0.022	-.0292	.946	0.3745
	(5.073)	(.098)	(-2.960)	(162.93)	
Japan	3.30	0.790	-.0482	.516	0.9864
	(5.288)	(9.652)	(-10.410)	(3.804)	
Norway	14.93	-.629	.0147	.878	0.4110
	(4.292)	(-1.526)	(1.056)	(15.882)	
UK	13.31	-.376	-.0131	.856	0.2850
	(9.309)	(-2.253)	(-2.889)	(12.648)	

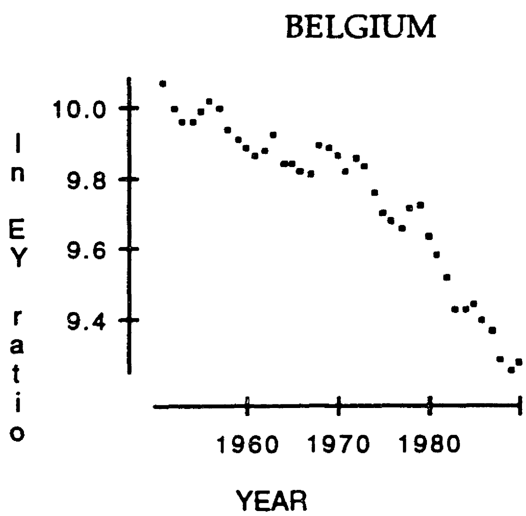
Country	$\hat{\alpha}'$ (t-statistic)	$\hat{\beta}_1$ (t-statistic)	$\hat{\beta}_3$ (t-statistic)	$\hat{\rho}$ (t-statistic)	R-square
Brazil	8.81	-.038	.0023	.572	0.9382
	(9.732)	(-.300)	(.522)	(5.016)	
Cameroon	1.20	0.921	.0318	.586	0.8359
	(.359)	(1.804)	(2.082)	(4.033)	
Chile	11.62	-.346	.0072	.809	0.4607
	(10.289)	(-2.447)	(1.642)	(8.291)	
India	14.31	-.960	.0346	.773	0.8750
	(15.778)	(-6.634)	(10.745)	(7.723)	
Kenya	8.97	-.004	-.0196	.705	0.3666
	(6.229)	(-.017)	(-3.656)	(8.957)	
Korea	11.92	-.351	.0132	.910	0.6629
	(9.250)	(-1.653)	(.699)	(66.740)	
Mexico	12.77	-.530	.0272	.803	0.7932
	(8.860)	(-2.869)	(5.067)	(8.758)	
Morocco	13.97	-.857	.0311	.791	0.4499
	(6.817)	(-2.767)	(2.855)	(8.625)	
Nigeria	9.23	-.362	.0528	.741	0.5525
	(4.896)	(-1.221)	(4.860)	(6.826)	
Philippines	8.51	0.03	-.0036	.917	0.1666
	(3.005)	(.073)	(-.267)	(27.447)	
Tunisia	10.08	-.201	.0180	.515	0.8762
	(4.710)	(-.656)	(1.489)	(3.672)	
Uganda	14.21	-.853	-.0153	.918	0.1199
	(10.456)	(-4.609)	(-1.989)	(41.614)	

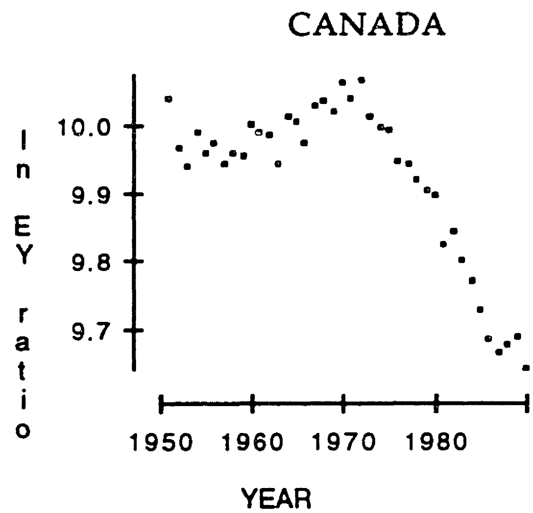
Appendix D

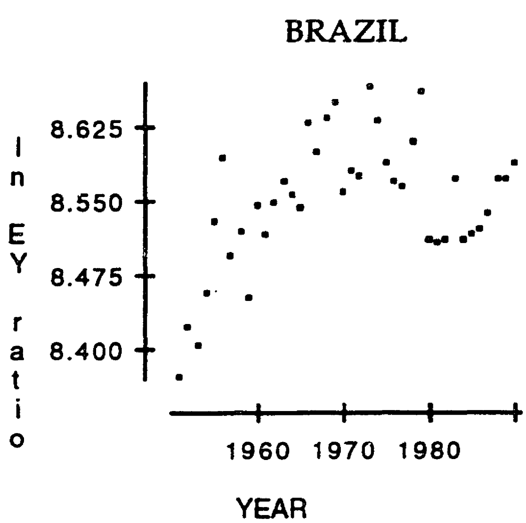
Aggregate Energy-Income Trends by Country

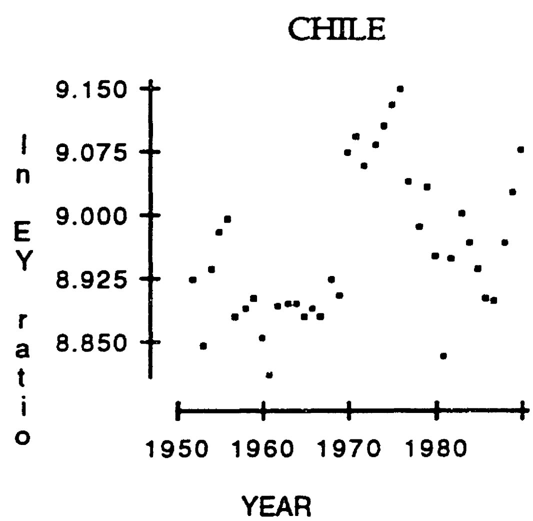

AUSTRALIA
9.600
9.525
9.450
9.375
9.300
ln EY ratio
1960 1970 1980
YEAR


CAMEROON
8.8
8.4
8.0
7.6
ln EY ratio
1960 1970 1980
YEAR

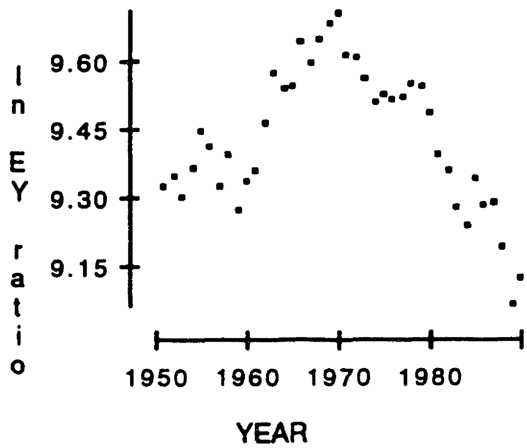

BELGIUM
10.0
9.8
9.6
9.4
ln EY ratio
1960 1970 1980
YEAR


CANADA
10.0
9.9
9.8
9.7
ln EY ratio
1950 1960 1970 1980
YEAR

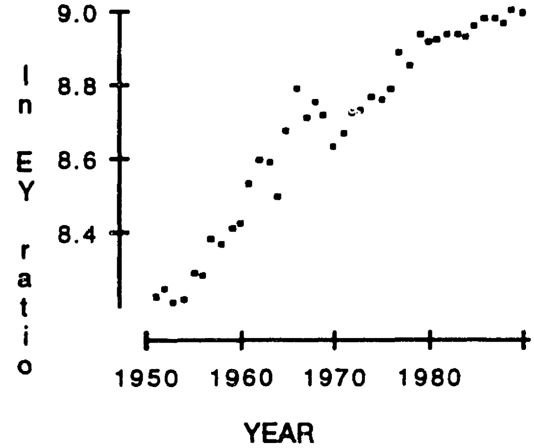

BRAZIL
8.625
8.550
8.475
8.400
ln EY ratio
1960 1970 1980
YEAR


CHILE
9.150
9.075
9.000
8.925
8.850
ln EY ratio
1950 1960 1970 1980
YEAR

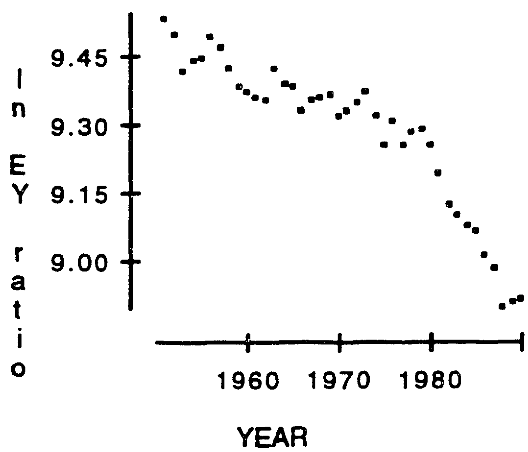
DENMARK



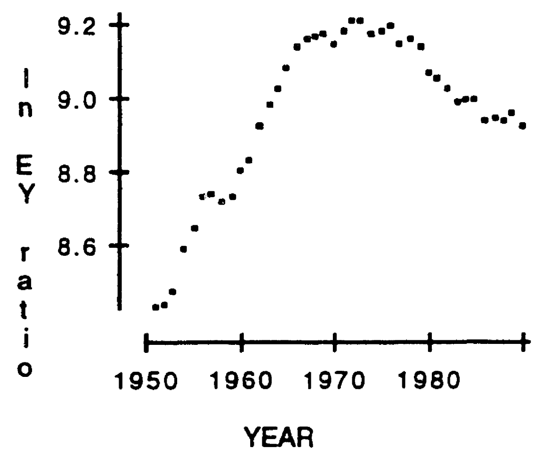
INDIA



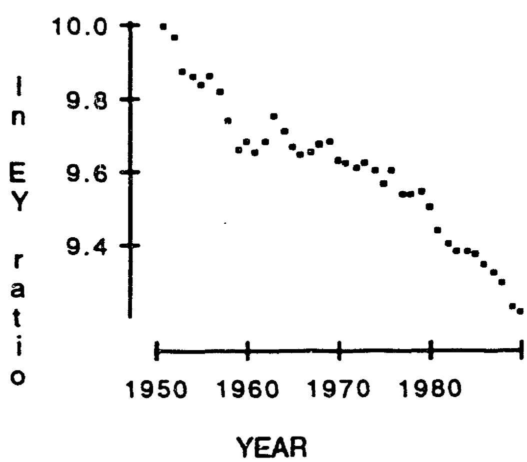
FRANCE



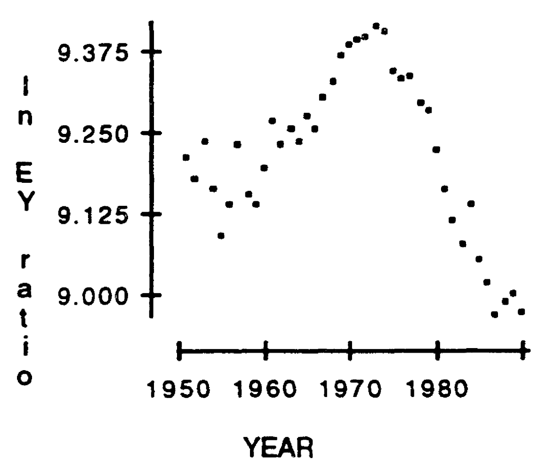
ITALY



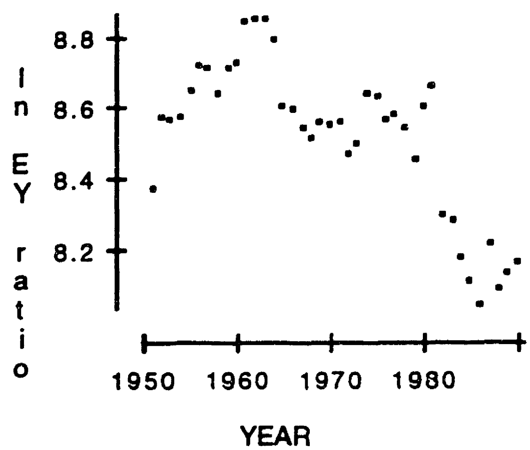
GERMANY



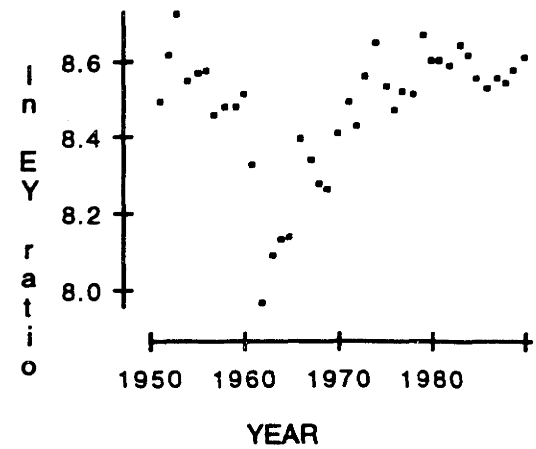
JAPAN



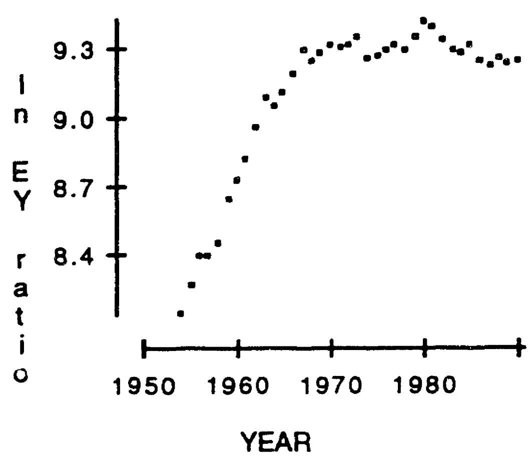
KENYA



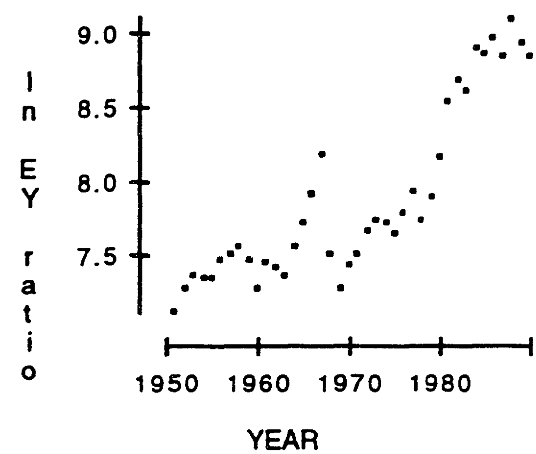
MOROCCO



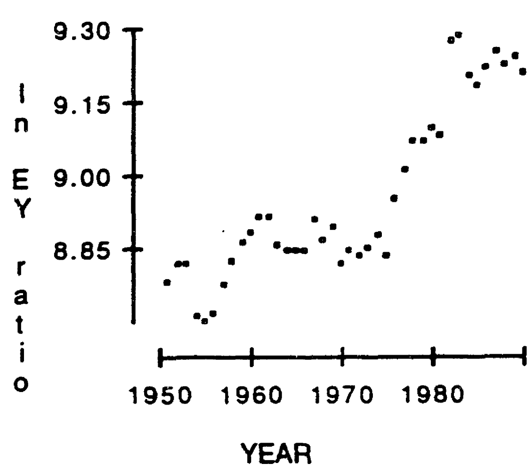
KOREA



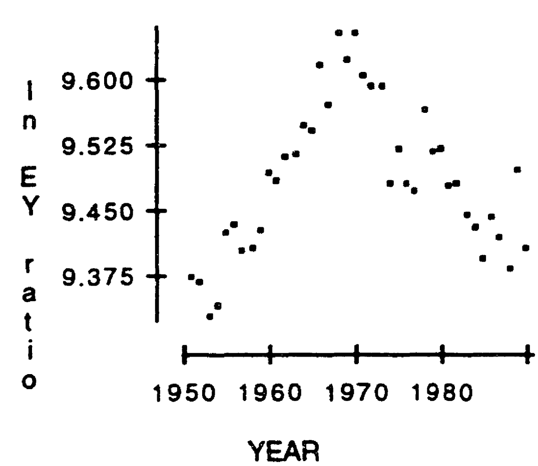
NIGERIA

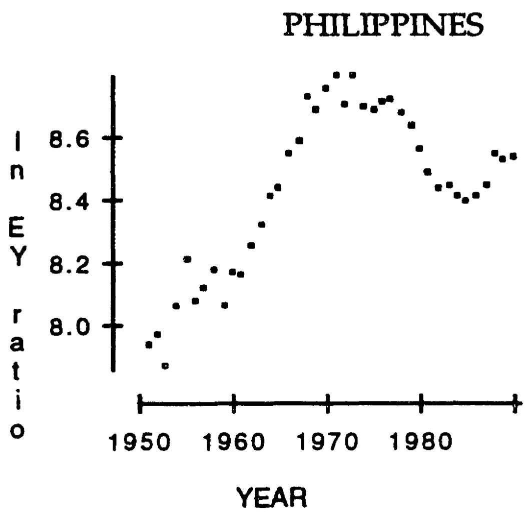


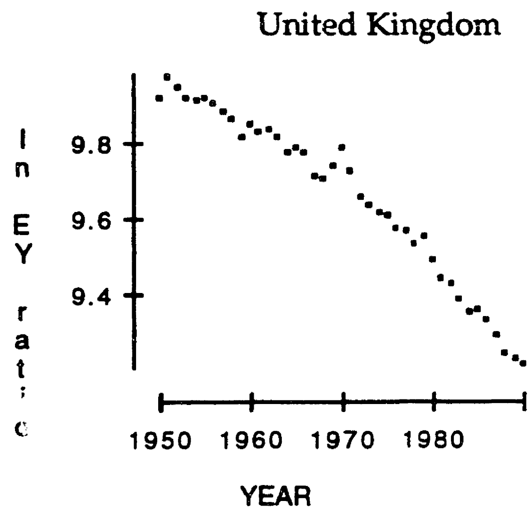
MEXICO

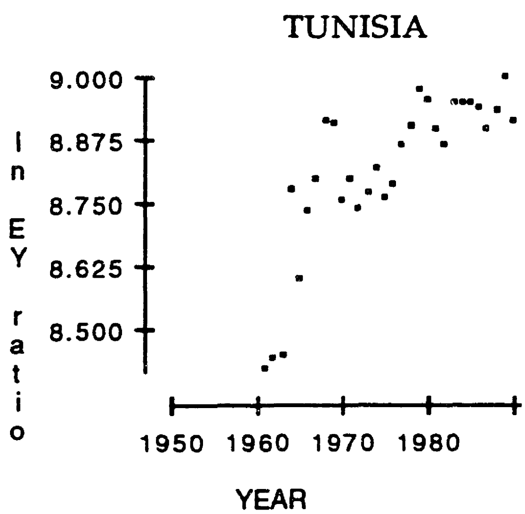


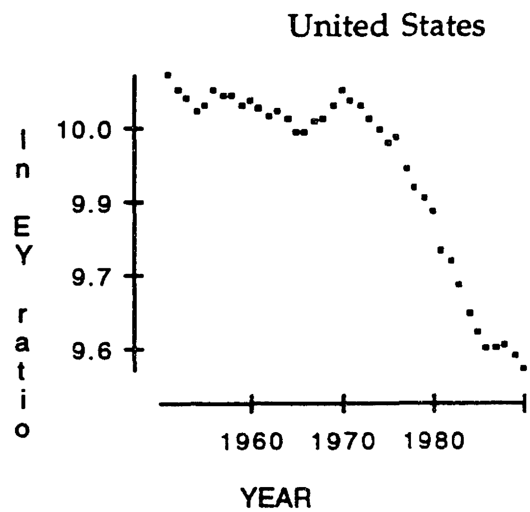
NORWAY

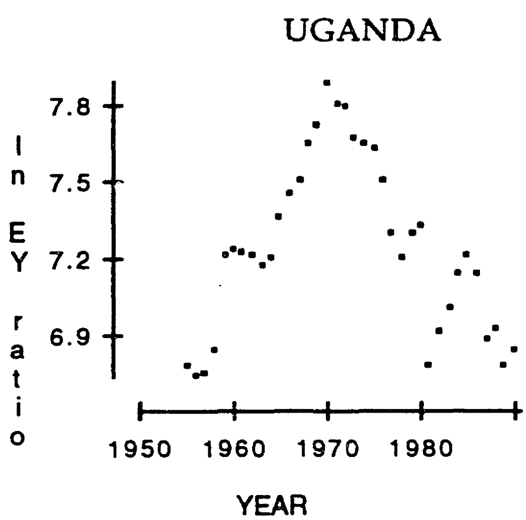



PHILIPPINES
ln EY ratio
8.6
8.4
8.2
8.0
1950 1960 1970 1980
YEAR


United Kingdom
ln EY ratio
9.8
9.6
9.4
1950 1960 1970 1980
YEAR


TUNISIA
ln EY ratio
9.000
8.875
8.750
8.625
8.500
1950 1960 1970 1980
YEAR

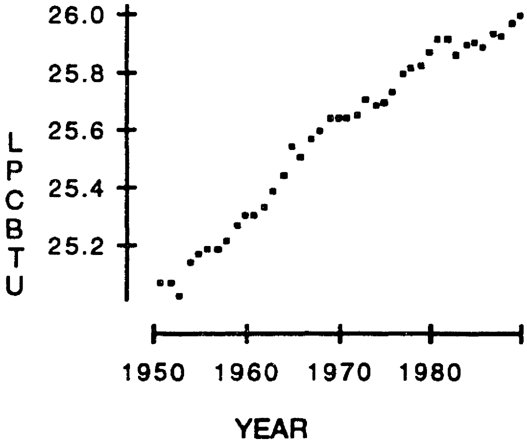

United States
ln EY ratio
10.0
9.9
9.7
9.6
1960 1970 1980
YEAR


UGANDA
ln EY ratio
7.8
7.5
7.2
6.9
1950 1960 1970 1980
YEAR

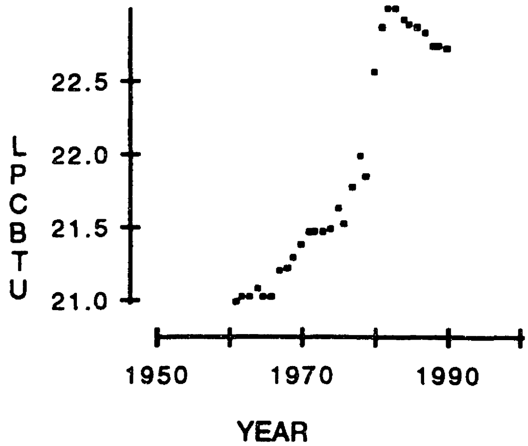
Appendix E

Per Capita Energy Consumption Trends by Country

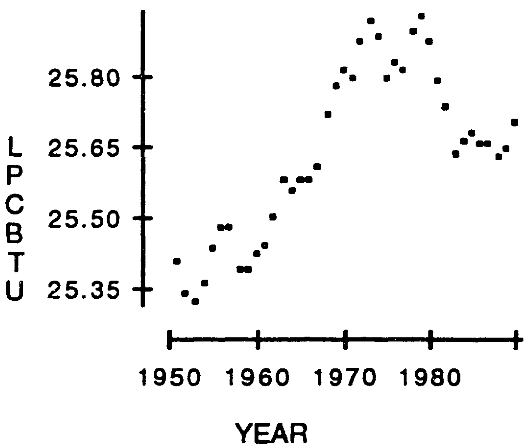
AUSTRALIA



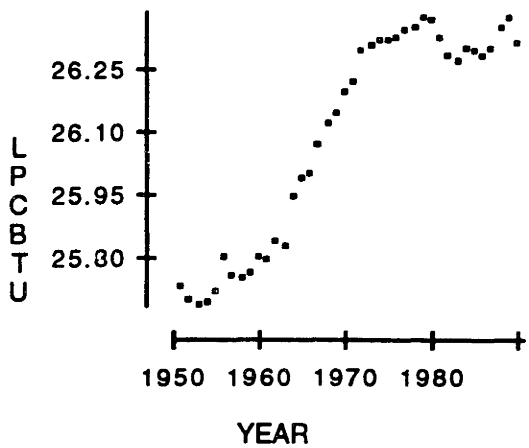
CAMEROON



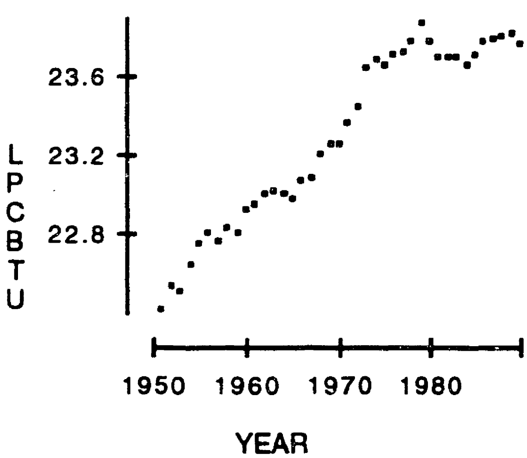
BELGIUM



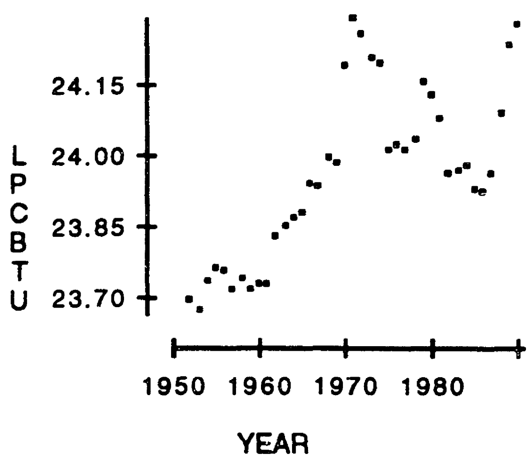
CANADA



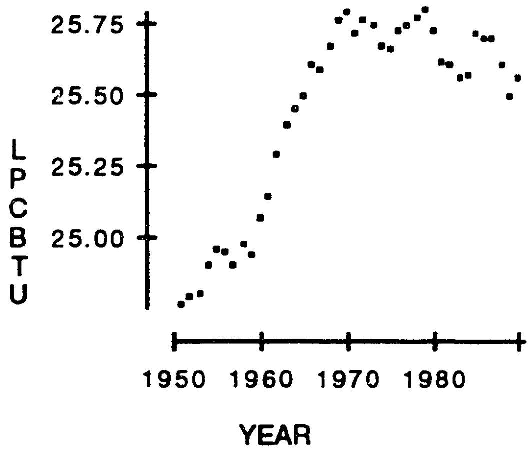
BRAZIL



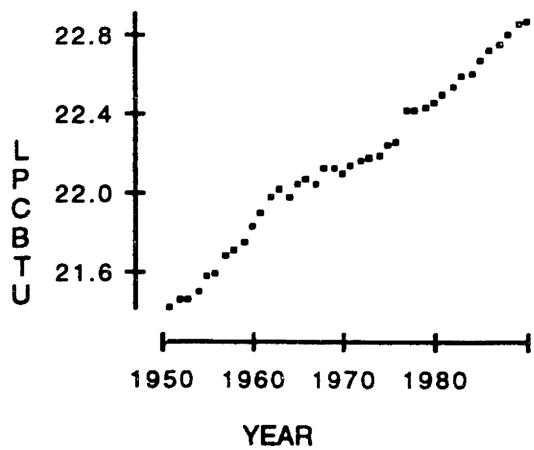
CHILE



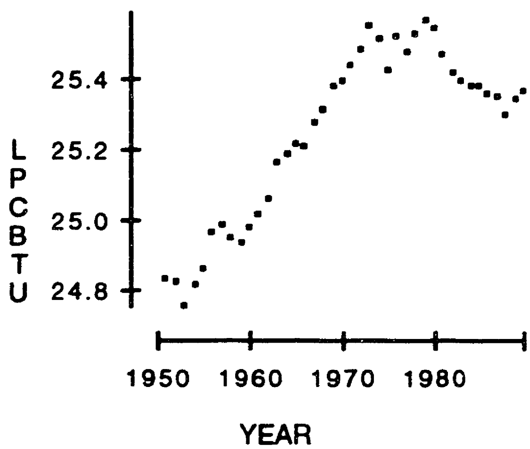
DENMARK



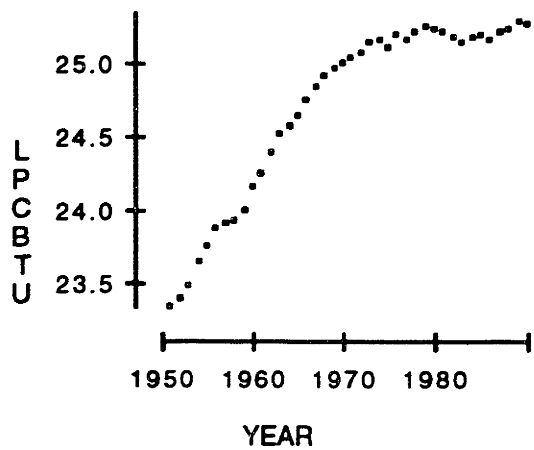
INDIA



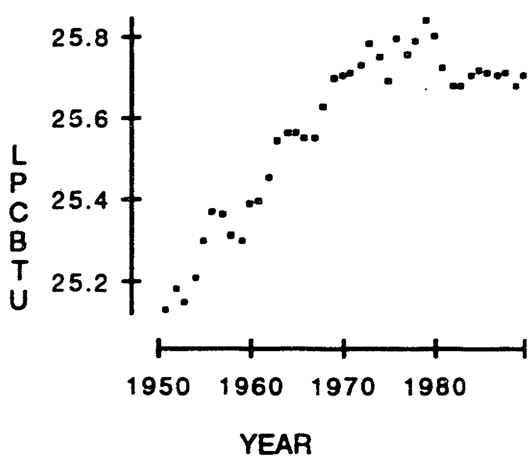
FRANCE



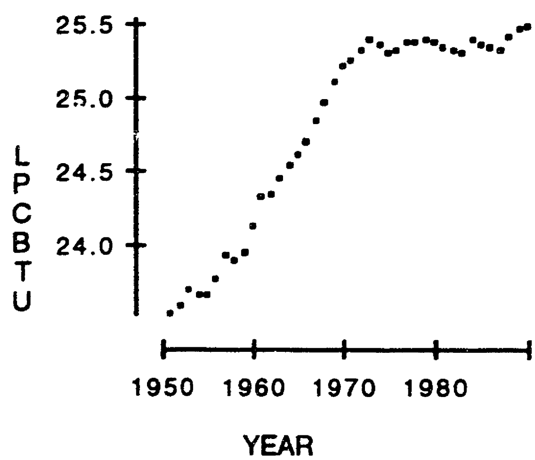
ITALY



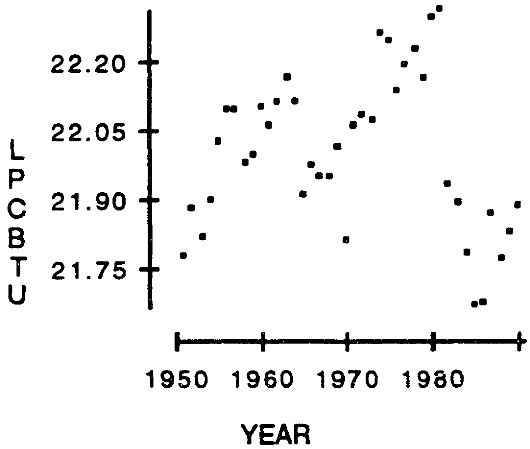
GERMANY



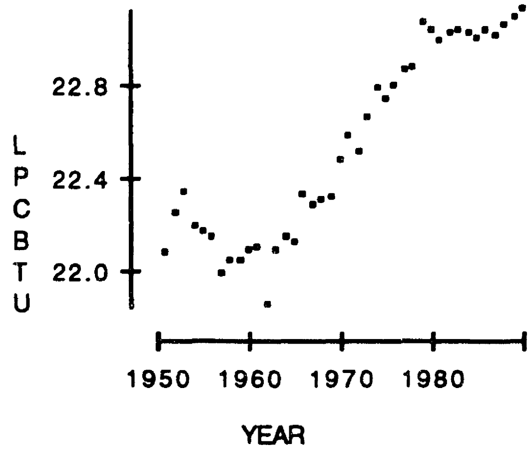
JAPAN



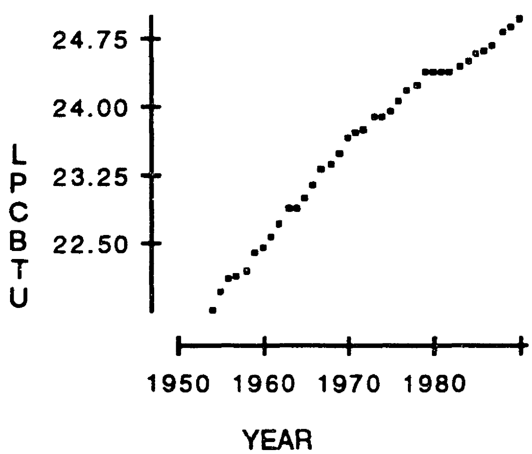
KENYA



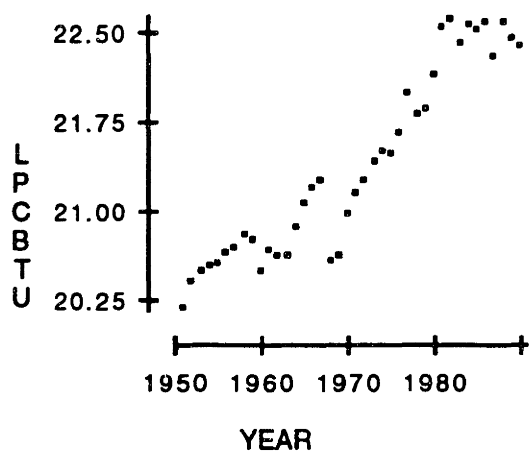
MOROCCO



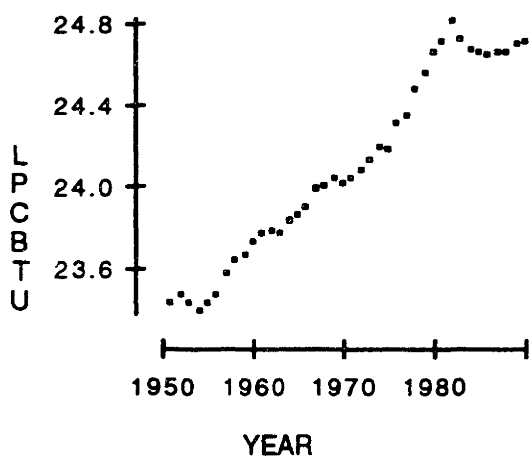
KOREA



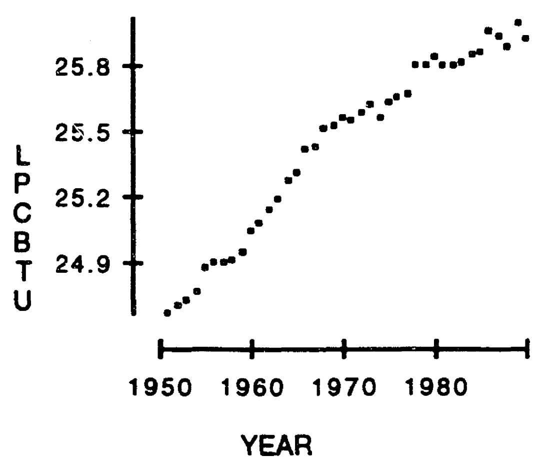
NIGERIA

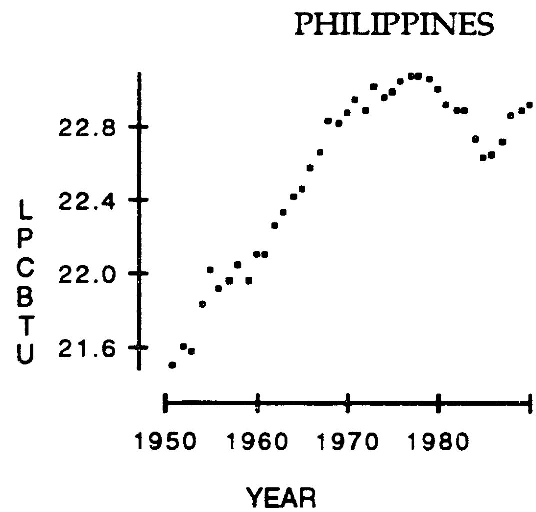


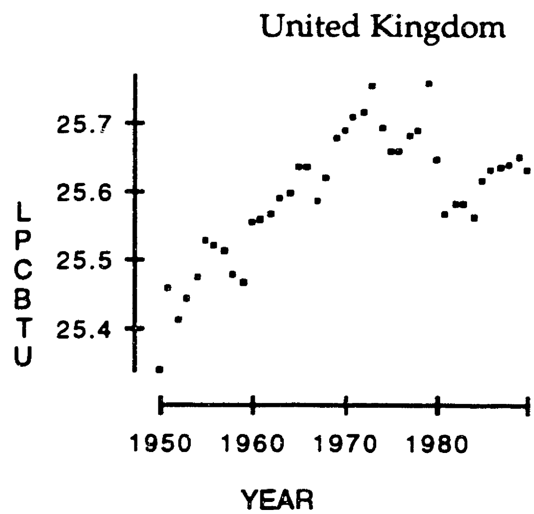
MEXICO

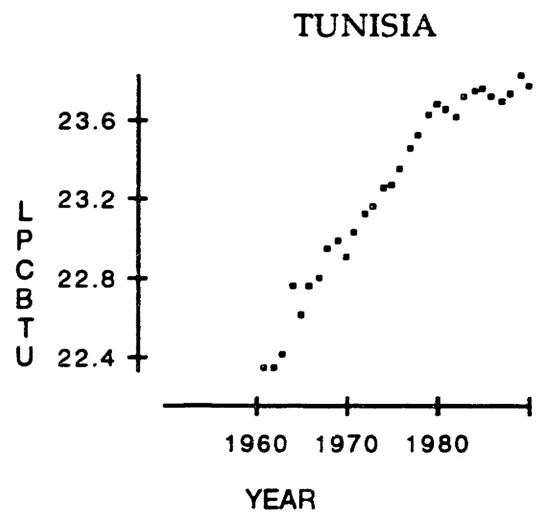


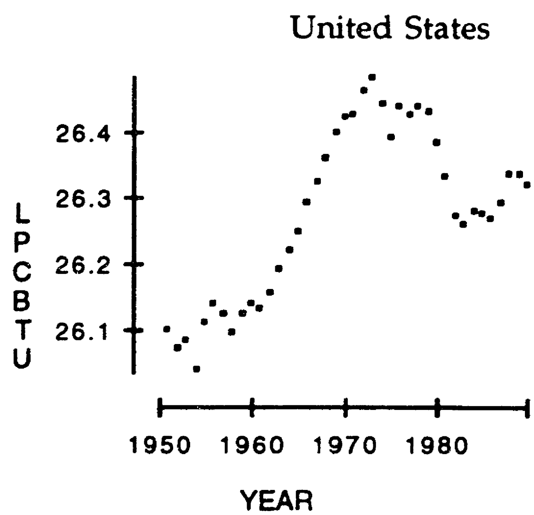
NORWAY

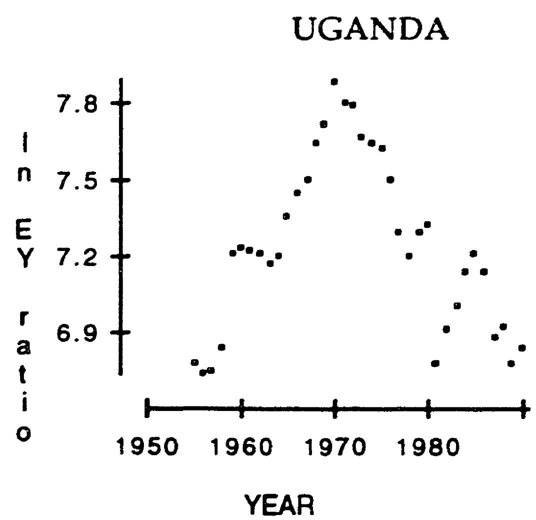



PHILIPPINES
LPCBTU
22.8
22.4
22.0
21.6
1950
1960
1970
1980
YEAR


United Kingdom
LPCBTU
25.7
25.6
25.5
25.4
1950
1960
1970
1980
YEAR


TUNISIA
LPCBTU
23.6
23.2
22.8
22.4
1960
1970
1980
YEAR

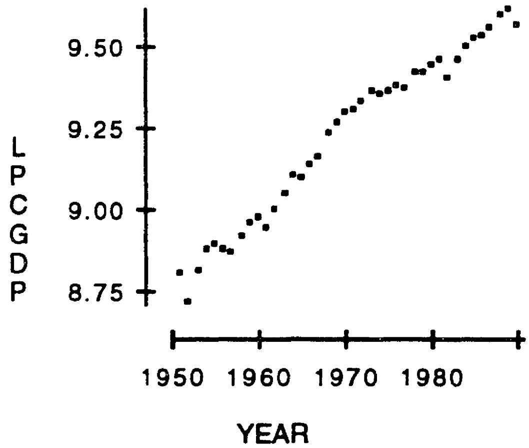

United States
LPCBTU
26.4
26.3
26.2
26.1
1950
1960
1970
1980
YEAR


UGANDA
ln EY ratio
7.8
7.5
7.2
6.9
1950
1960
1970
1980
YEAR

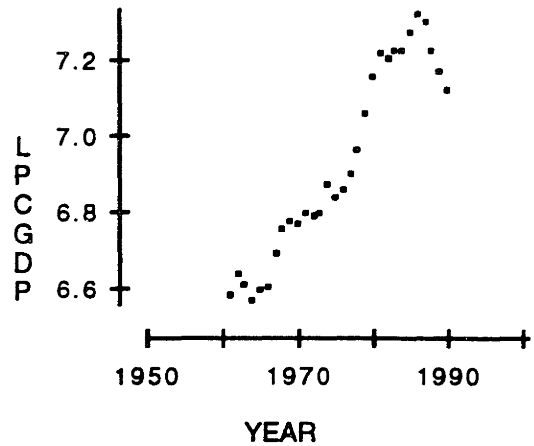
Appendix F

Income per Capita Growth by Country

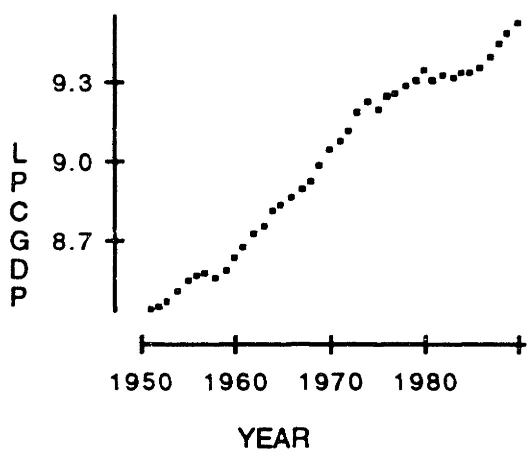
AUSTRALIA



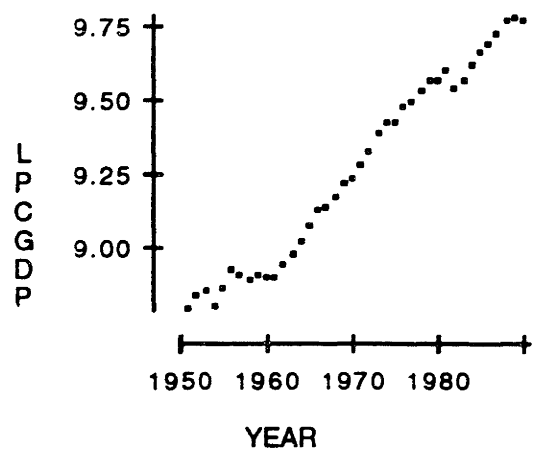
CAMEROON



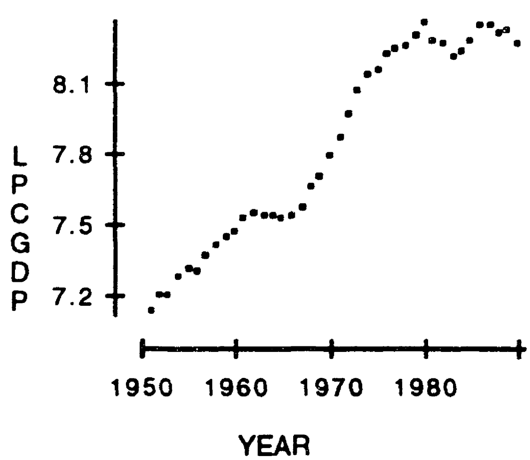
BELGIUM



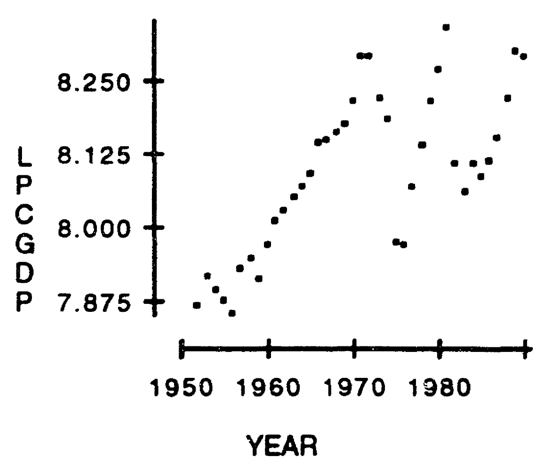
CANADA



BRAZIL



CHILE



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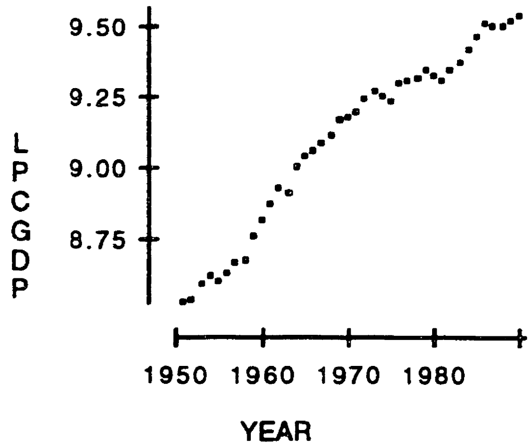

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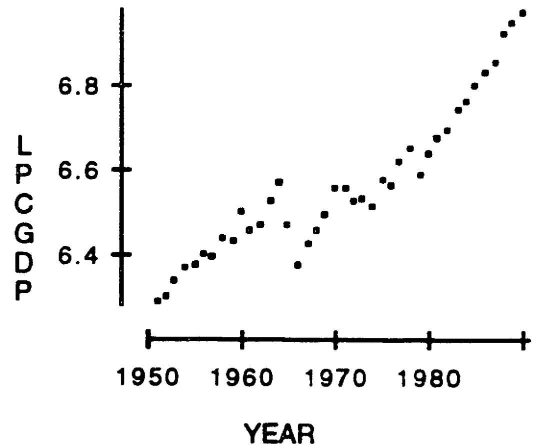

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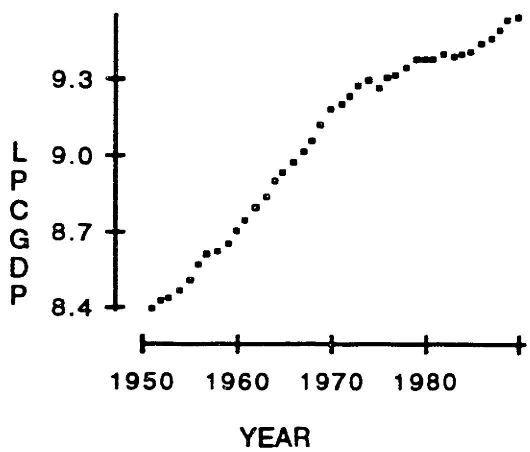

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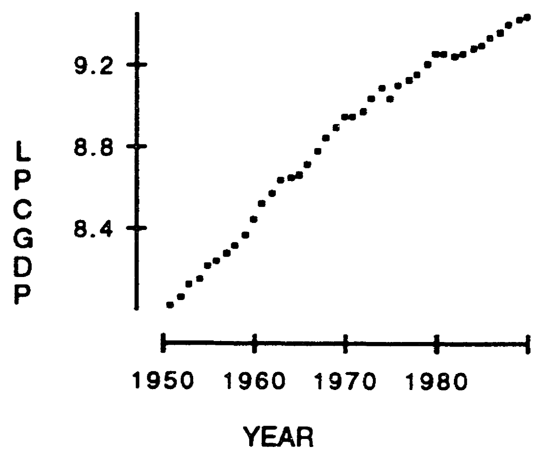

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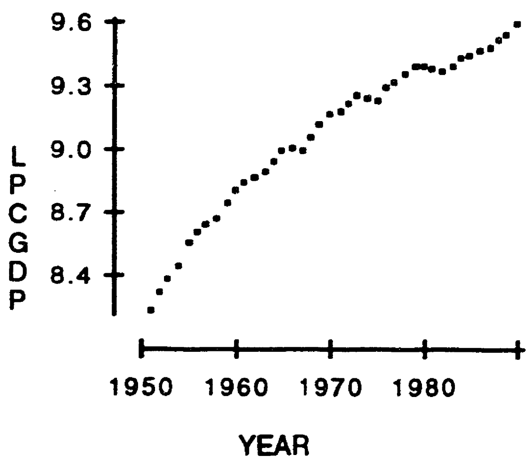

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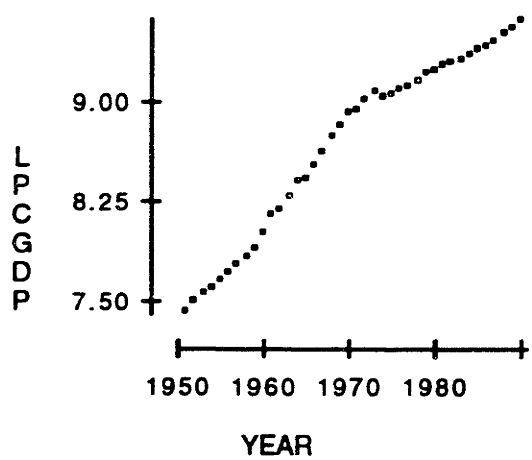

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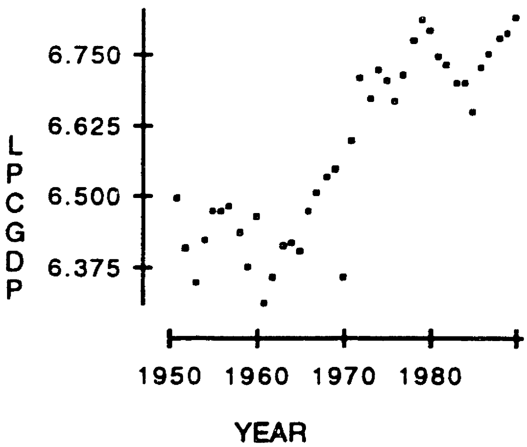

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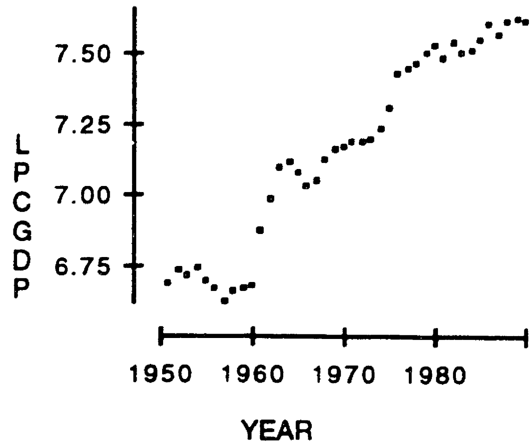

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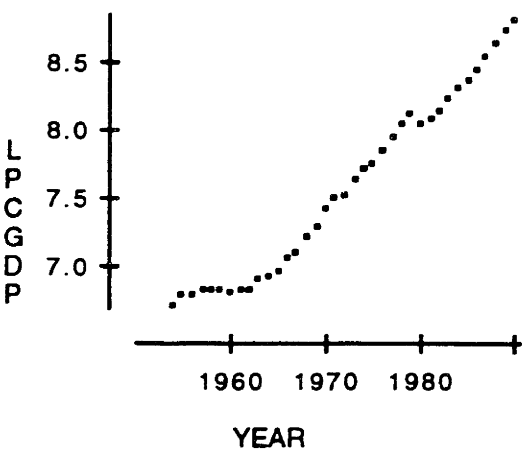

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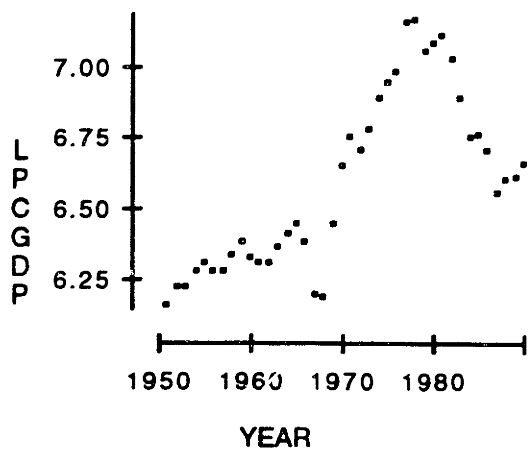

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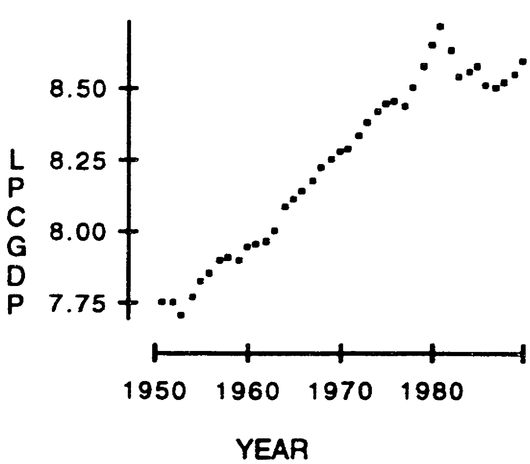

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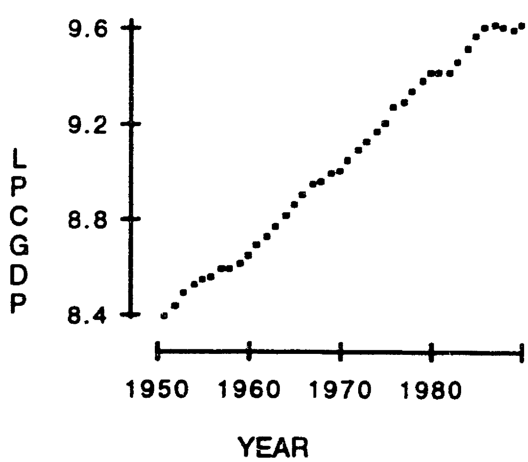

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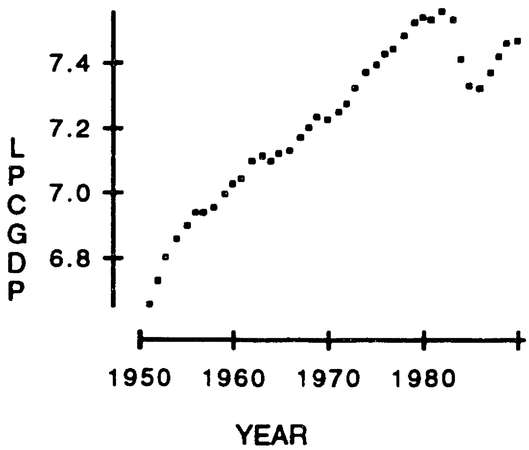

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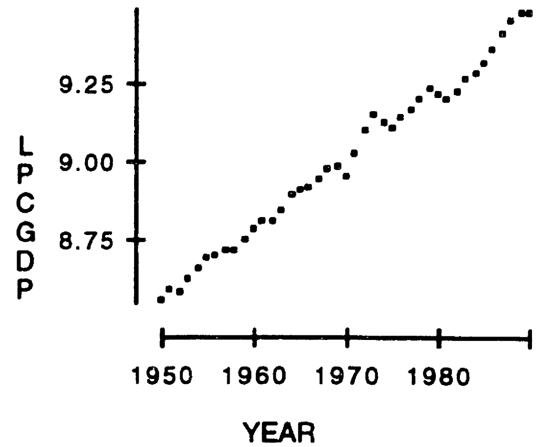

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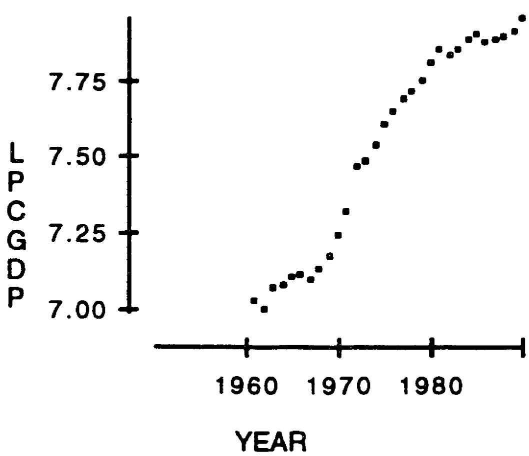

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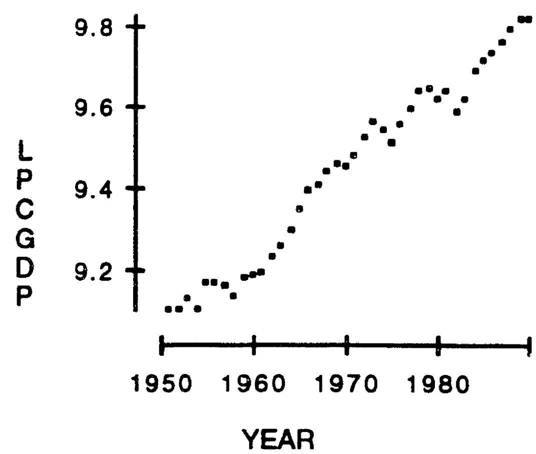

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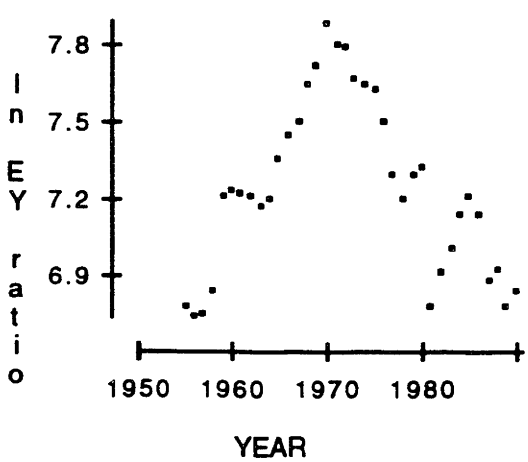

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