Empirical Relations in the World Electrical System

John H. Walsh
Energy Advisor

Abstract

In Chapter 13 of the 'World Energy Outlook 2002' titled *Energy and Poverty*, the International Energy Agency stresses the important role of energy and particularly that of electricity in the alleviation of world poverty. This paper was prepared in part as a preliminary exploration of factors relevant to the world electrical situation. The ratios of net electrical generation to various likely parameters of interest were plotted over the past decades to search for unexpected empirical relationships that may be useful in gaining some insight into the world energy economy. Straight-line segments were found when the ratios of world generation to primary energy, generation per capita, and carbon dioxide emissions per unit of electricity generated were plotted over time. A second purpose of this paper was to determine whether this approach is useful in the study of the possible dematerialization of the world economy.

Net electrical generation remains strongly linked to economic growth and, as a measurable and unchanging physical unit, could serve as a surrogate for world GDP without the complexities and inaccuracies of currency exchange corrections, purchasing power parity adjustments, etc., which plague its measurement. It is difficult to distinguish dematerialization from normal autonomous increases in energy efficiency because both reduce energy consumption per unit of GDP though these two processes are conceptually quite different. Nevertheless, because a dematerialized economy would still have a strong need for electricity, there is the possibility that the distinction between these two processes could be detected from plots of this kind. No strong evidence for dematerialization could be found in this paper but the trends resulting from plotting net electrical generation to world steel and to cement production over time were perplexing in that the two ratios behaved quite differently.

Introduction

The *World Energy Outlook 2002* is one of a series published by the International Energy Agency every two years. The new edition explores the world energy system for the near future up to 2030, and deals with broader issues than previous reports such as energy security and world poverty. Chapter 13 entitled *Energy and Poverty* was released in advance of the full 2002 outlook so as to be in time for presentation to the World Summit on Sustainable Development held in Johannesburg, South Africa, 28 August to 4 September, 2002.[1] This interesting document of 46 pages (including references and extensive tables) provides new country-by-country data on electrification rates worldwide with projections to 2030 and sets out a quantitative framework for strategies for the alleviation of poverty. This chapter reveals that some 1.6 billion people – one-quarter of the world's population – have no access to electricity at present. Without new policies, 1.4 billion will still lack electricity in 2030. Some 2.4 billion people rely on traditional biomass – wood, agricultural residues and dung – for cooking and heating. This number is expected to actually *increase* to 2.6 billion by 2030. The IEA is surely right when it states that the lack of electricity exacerbates poverty and contributes to its perpetuation, as it precludes most industrial activities and related economic growth.

Electrical production may be expressed as net generation, gross generation, and consumption, and it is necessary to choose among these three broad possibilities before selecting the parameter to represent world electricity supply. Consumption data is usually about 7% less than published generation values in that in the main it reflects transmission losses. Generation data is preferred to consumption data for this purpose because there are markedly fewer `generators' than `consumers.' Since there is effectively negligible storage in the electrical system, there is no inventory to change over time and thus production and consumption should always be strongly and instantaneously linked. There is good reason to believe that generation is measured carefully as a normal operating procedure at most electrical stations.

However, it is also true that it is the electricity actually consumed that is demanded by the economy (the buyer is concerned with what is received not transmission losses) and, were it not for the problem of statistical accuracy, this value would have been preferred for linking to the various economic parameters. The issue of this choice may become more important when distributed generation becomes a greater fraction of the world supply in the future.

Of the two possible values for generation, the net data was selected because gross-to-net generation data depends upon the characteristics of individual stations. Moreover, net generation is what the power producer is paid for so there is a strong incentive to get this number right.

The recent data for world supply (after 1985) was obtained from publications of the Energy Information Administration of the U.S. Department of Energy. Data for 1975-1985 was taken from the United Nations *Energy Statistical Handbook*. Earlier data for 1960 to 1974 was taken from the United Nations *World Energy Supplies 1950-1974, Statistical Papers Series J No. 19* which did not specify whether the values were net or gross. This latter time series was, however, seamless with the later net generation data. The consolidated data series prepared was reasonably compatible with that published on the Web for 1970-2001 by the Uranium Information Centre Ltd. Nevertheless, for the years before 1980, there is not good agreement with data published in the World Bank Database. No reason for this discrepancy is known: an inquiry to the World Bank on this matter has gone unanswered.

In the energy field, it is widely believed that the link between primary energy consumption and economic growth is gradually being broken. This simple interpretation of the situation is challenged by authors such as Cleveland et al[2] who believe a strong link still exists but that primary energy needs to be re-defined to reflect the quality of the energy involved. Whatever this situation, a close link still exists with electrical demand.

The premise of this paper is that net electrical generation should serve as a proxy for GDP to at least a first approximation. The advantage of this measure is that it is expressed in physical units that are the same everywhere and unchanging over time. Thus there is no need to make uncertain conversions based upon currency exchange values and purchasing power parities when making comparisons among nations in very different economic circumstances.

There is a school of thought that believes the world economy is dematerializing especially in the developed nations. If so, one would expect the link between primary energy and GDP would be loosening but that between electricity and GDP would still remain valid since electricity is required in a post-industrial society as well as in a conventional one. There is a major problem, however, in distinguishing between changes due to normal autonomous gains in efficiency on the one hand and dematerialization on the other. Although these processes are conceptually very difficult, the measured effect on the GDP/Primary Energy ratio would appear to be the same for both hypotheses. Because electricity will still be needed to some degree in the newly dematerialized sector of the post industrial economy, there is the possibility that plots involving electrical generation ratios to various relevant parameters would help reveal this distinction. Unfortunately, the graphs that follow cannot be said to reveal this difference but it may be that the range of data available simply does not lead to measurable effects as yet to allow this differentiation to be drawn.

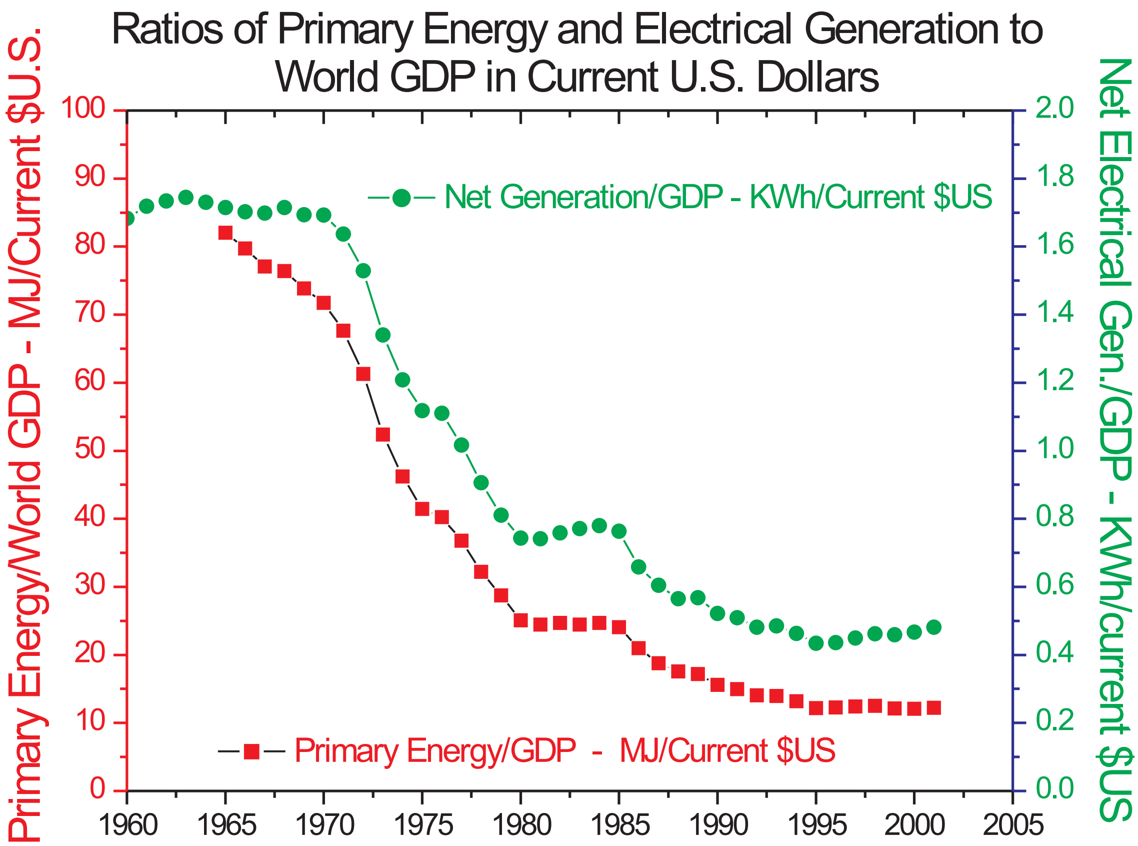

Figure 1: Ratios of Primary Energy and Electrical Generation to World GDP

The ratios of primary energy to world GDP and net electrical generation to world GDP are plotted together in Figure 1. The data for world GDP (expressed in current U.S. dollars) was obtained from the World Bank information service. The Bank also provided the following statement when asked about the provenance of the statistics:

> `GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in current U.S. dollars. Dollar figures for GDP are converted from domestic currencies using single year official exchange rates. For a few countries where the official exchange rate does not reflect the rate effectively applied to actual foreign exchange transactions, an alternative conversion factor is used.'

The plot shows that the two ratios move together over the time period studied. The steady fall in the values is presumably a measure of inflation during this time. It cannot be said that there is any evidence of diverging behaviour of the electrical from the primary energy data over this period but a strong link between the two was found in Figure 2.

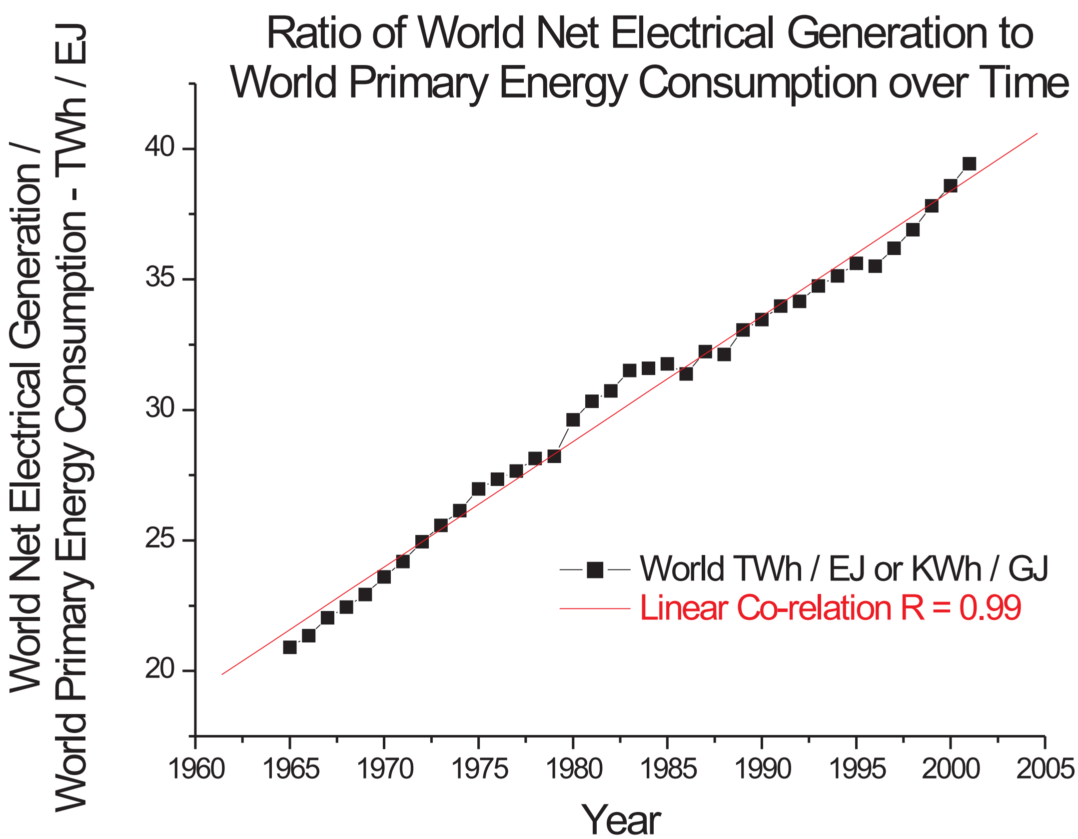

Figure 2: Ratio of World Net Electrical Generation to World Primary Energy Consumption

The ratio of world net electrical generation to world primary energy consumption was found to follow a straight line from 1965 to 2001 with a good correlation between the ratio and the date of R = 0.99 (Y axix dependent variable). The primary energy consumption was calculated from data published yearly in the *BP Statistical Review of World Energy* which excludes energy derived from the biomass as well as all non-commercial forms of energy that may be consumed in the world.

Primary electricity (hydro and nuclear) and the inputs to fossil-based generation are included in the primary energy data appearing in the denominator of the ratio. An upward trend in the curve could be explained in part on an increased efficiency in the generation of electricity from its fossil fuel inputs.

It may be that the line is starting to deviate upwards from 1996 onwards. Such a trend would be expected if the generation of electricity remains strongly linked to GDP while the link between the consumption of primary energy and GDP is starting to decouple so as to weaken the underlying factors that have led to this co-relation in the first place. The economy may be consuming less primary energy per unit of GDP because of gains in efficiency or because of dematerialization. Perhaps both effects are occurring at the same time.

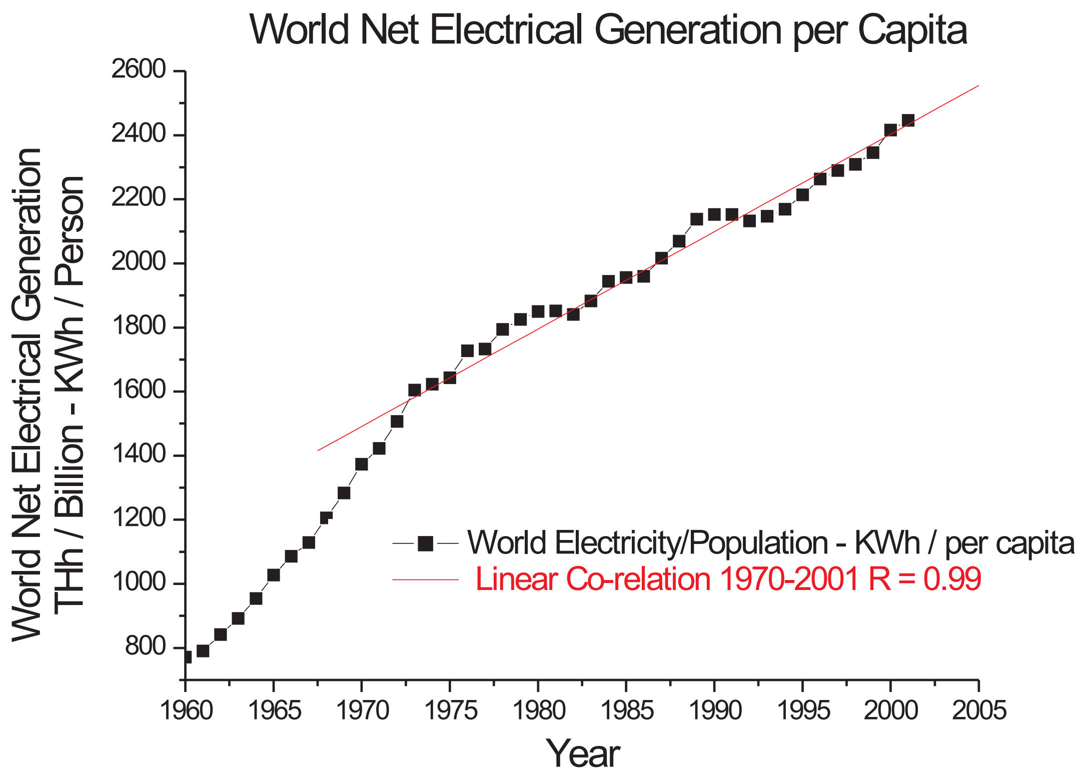

Figure 3: World Net Electrical Generation per Capita

The per capita net generation was calculated using world population data obtained from the *CIA World Factbook* and from United Nations sources for the earlier years. The results were calculated in terms of TWh/billion which is equal to KWh/Person.

Though gently undulating, world net electrical generation per capita was found to be essentially a linear function of time over the period 1970 to the present ($R = 0.99$). Previous to 1970, the curve appears to be following a slowly increasing exponential curve as would be expected to result from the ratio of two such curves – exponentially growing electrical generation divided by exponentially growing population. Between 1970 and 2002, the per capita net generation of the world could have been determined with reasonable accuracy knowing only this line and the date. The issue is whether this effect is predictive, that is, for how long this straight-line period will persist. It will be interesting to continue this plot in subsequent years. Why the exponential relationship ends about 1970 to be followed by a straight-line section is unclear but both the growth of world generation and population began to slow during this period.

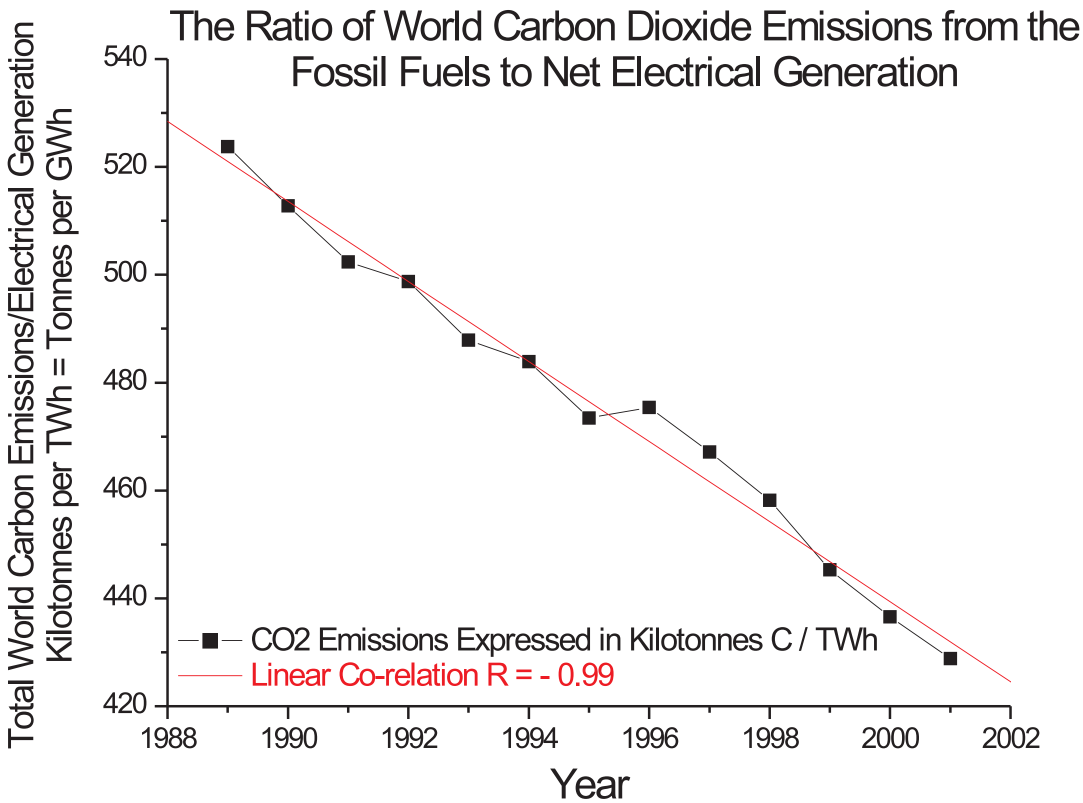

Figure 4: The Ratio of World Carbon Dioxide Emissions from the Fossil Fuels to Net Electrical Generation

Carbon dioxide emissions (counted as contained carbon) calculated from world fossil fuel consumption are plotted as a ratio of the net electrical generation over time in Figure 4. A good declining straight line is obtained for the thirteen-year period from 1989 to 2001 (R = - 0.99). The carbon emissions were calculated from the *BP Statistical Review of World Energy* by applying standard coefficients to energy consumption data. This data was calculated and reported each June by this author in a series of yearly *Carbon Dioxide Fact Sheets.*[3]

This plot suggests that world carbon dioxide emissions fall with total electrical generation in a regular way though it must be noted that the data covers only thirteen years. (The plot involves the world total carbon emissions not just those released in the generation process itself.) To the extent that electrical generation serves as a proxy for GDP, the graph suggests wealth is increasing faster than the emissions of this greenhouse gas. World per capita emissions for each date can be computed by multiplying this data by the data in Figure 3. If these two straight-line relationships hold over time, it follows that world per capita emissions will fall over time. It is a matter of some interest to the control of emissions of carbon dioxide to see whether this trend continues in the future.

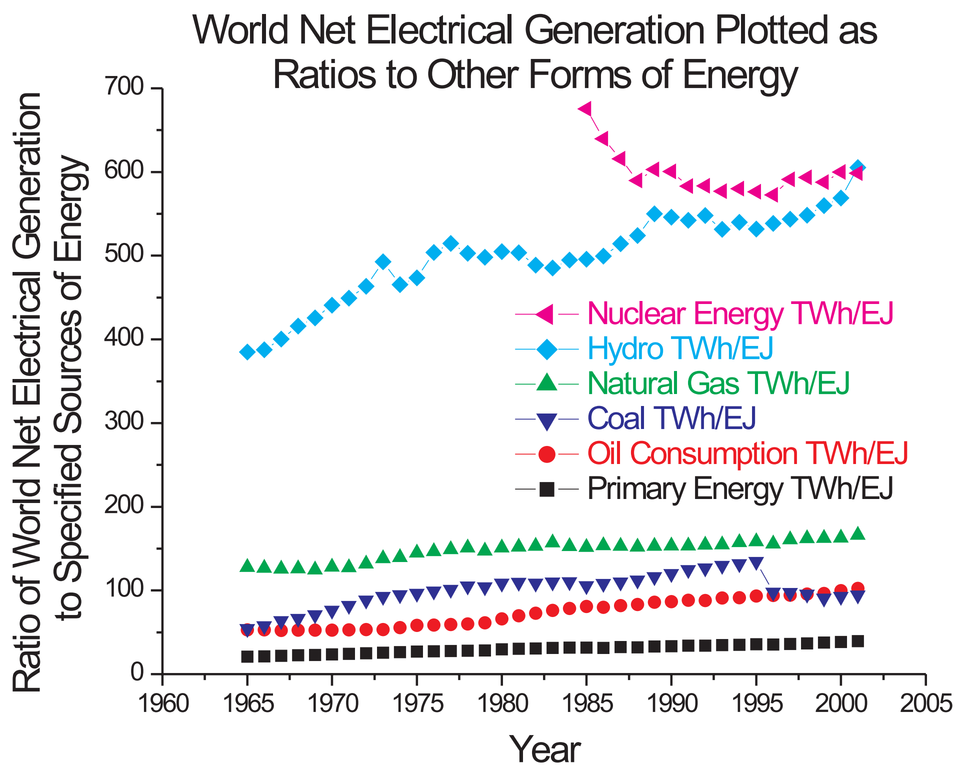

Figure 5: World Net Electrical Generation Plotted as Ratios to other Forms of Energy

The ratios of world net electrical generation to the consumption of the primary energy forms are plotted in Figure 5 for the period 1965 to the present except for nuclear primary energy which only become prominent in supply terms after 1985. The curves for primary hydraulic electricity, oil and coal suggest a rising trend. This trend suggests that total electricity is steadily becoming more important than hydro power (which is limited to the generation sites available), oil, and coal. The discontinuity in the coal curve is thought to be due to statistical problems with Chinese coal production which ranked second to only the U.S. in 2001. The curve for natural gas is flatter reflecting the growing importance of this convenient and somewhat benign fuel. The marked fluctuations in the hydro curve as compared to the others might well reflect the dependence of this source of energy on variable weather conditions. The flatness of the nuclear curve after 1990 is probably due to the rapid expansion of this industry around the globe but this curve may well rise in the future.

It is possible the extrapolation of plots of this kind would be predictive for at least the near-term future.

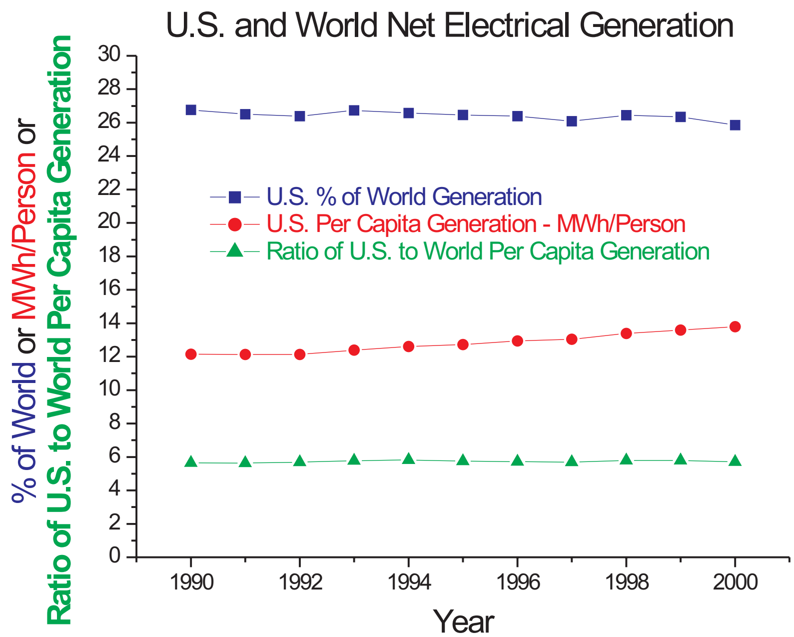

Figure 6: U.S. and World Net Electrical Generation

The plot of U.S. and World Net Electrical Generation in Figure 6 was prepared because of the importance of U.S. generation in the world total at about 25-26%. It is possible that the U.S. percentage to the total and the ratio of U.S. to world per capita generation are declining somewhat over time although the data extends only over eleven years. There is little doubt, however, that U.S. per capita generation is still gently rising.

This plot provides a check on estimates of possible world electrical requirements in the future. It may be assumed that world generation in 2050 will be at least 25% of the U.S. per capita figure of 13790 KWh/person in 2000. This approach would set a minimum value for the world of 3447 KWh/person in 2050. Assuming world population increases to at least eight billion in 2050, the generation in that year would be 27580 TWh. If world per capita generation were to reach 50 or 75% of the value of U.S. per capita level in 2000 by 2050, world generation would then be 55160 and 82740 TWh respectively.

The study by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council entitled *Global Energy Perspectives* published in 1998 employs a population scenario that reaches 10.06 billion for the world in 2050.[4] This value is now generally considered too high. The electricity component of the final energy requirement for the six IIASA scenarios range from:

Scenario A1: 33494 TWh (3329 KWh/person)
Scenario A2: 36100 TWh (3588 KWh/person)
Scenario A3: 35239 TWh (3503 KWh/person)
Scenario B: 27214 TWh (2705 KWh/person)
Scenario C1: 20818 TWh (2070 KWh/person)
Scenario C2: 20004 TWh (1988 KWh/person)

These values are in the right range but the per capita numbers for ecologically-driven Scenarios C1 and C2 appear too low. Scenario B is the closest to business as usual and the IIASA/WEC projected world generation of 27214 TWh may be compared with 27580 TWh for the 25% of U.S. in 2000 case above. However, the Scenario B projection of 2705 KWh/person does not check well with the 3447 KWh/person for the 25% of U.S. 2000 values.

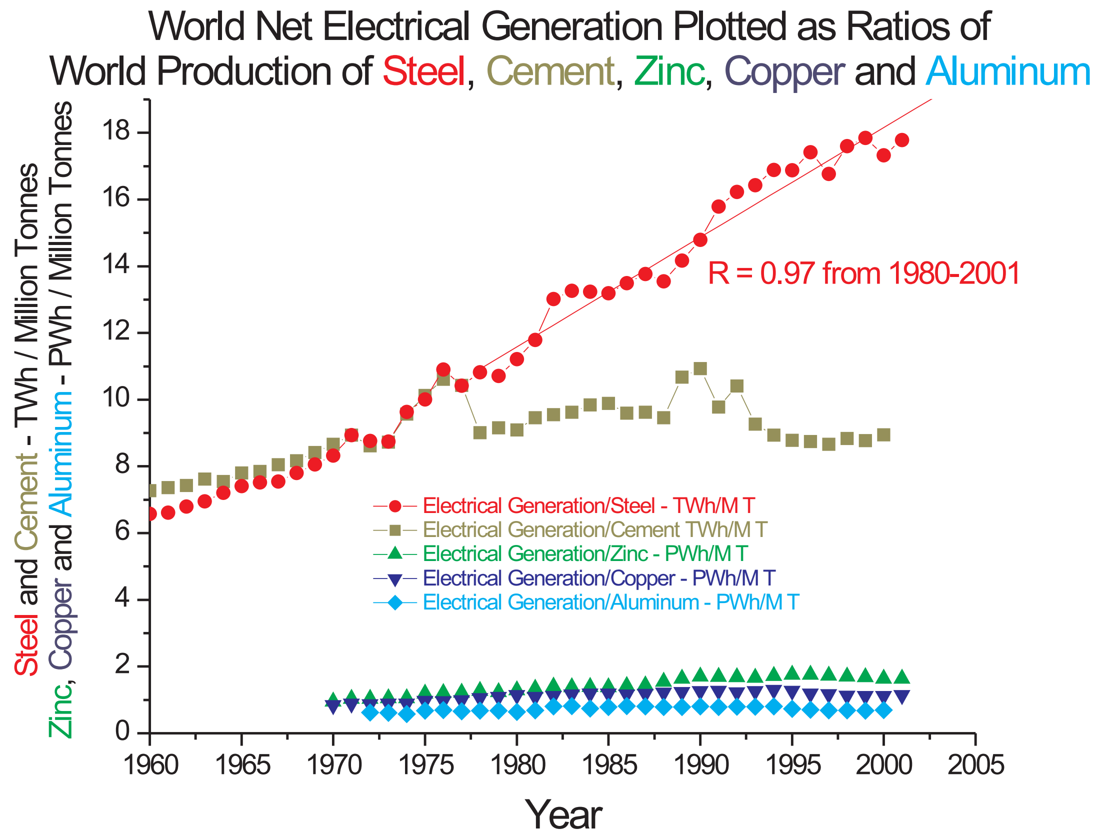

Figure 7: World Net Electrical Generation as Ratios of World Production of Steel, Cement, Zinc, Copper and Aluminum

Net electrical generation is plotted in Figure 7 as a series of ratios to production of a number of materials on a world basis. The values for steel were obtained from the International Iron and Steel Institute (1960 to present); those for cement (1960 to 2000) were taken from a tabulation prepared by van Oss and Kelly published by the U.S. Geological Survey; those for zinc metal production (1970 to 2001) from the International Lead and Zinc Study Group; those for copper mine production (1970 to 2001) from `The Copper Page'; and those for aluminum from the International Aluminium Institute (1972 to 2000). Unfortunately these values are not always consistent with other sources of information.

The ratio for electricity/steel behaves as one would expect in a dematerializing world with a straight-line relationship after 1990 (R= 0.97) but the behaviour of the ratio for electricity/cement is very different. No reason is known for this strong divergence in behaviour though it may be that even in a dematerializing world, the consumption of concrete would continue much as it has in the past because of its many uses in structures, houses, roads, etc. The ratio for electricity/zinc shows some signs of increasing as might be expected since one of its main uses is for galvanizing steel given that the ratio of electricity/steel is itself increasing rapidly. The ratios for electricity/copper and electricity/aluminum are changing only slowly over time and show no great evidence of dematerialization, at least over this time period.

The world production of the last three metals over this period might have been estimated by simply multiplying each nearly constant electricity/metal ratio by the net generation for each year.

Summary

The generation of electricity is still closely linked to GDP. Since world electrical statistics are expressed in an unchanging physical unit, there is the possibility that generation might serve as a surrogate for world GDP without the complexities and errors of compensating for inflation and currency equivalences among nations in very different economic circumstances. To test this hypothesis, net electrical generation was plotted as a ratio to several parameters of interest (electricity/primary energy, generation per capita, and carbon dioxide emissions/generation, electricity/some materials) in an effort to gain more insight into the electrical system because of its importance to reducing poverty around the world.

Straight-line segments were found in some of these graphs but it is uncertain how predictive such empirical relations could be in the sense of how long they will last over time. Nevertheless, another empirical relationship found earlier in the energy system revealed that world oil consumption per capita has been effectively a constant for the last 19 years.[5] Why such relationships persist in the world energy economy is not clear at present.

There is some evidence that the world economic system is gradually dematerializing but it is difficult to distinguish this effect from autonomous improvements in the efficiency with which energy is consumed. Because a dematerializing economy would still need electricity, the possibility exists that this distinction could be made between these two conceptually very different processes by comparing changes in primary energy consumption and electrical generation over time. It is also possible that the ratio of electricity generated to various other materials produced over time would also give indications. A confusing result was obtained in that ratios of electricity to steel and cement gave very different results. Plots involving other metals such as copper, zinc and aluminum showed no strong effect.

The main purpose of this paper is to report these exploratory correlations, not to explain them. It is the intention to follow these relationships over the next few years to check their validity into the future. It is evident from these graphs that a general theory of energy still eludes us.

References

1. World Energy Outlook 2002, Chapter 13, *Energy and Poverty*, International Energy Agency, Paris 2002. (Available on Web without charge at www.iea.org/)

2. Cutler J. Cleveland, Robert K. Kaufmann and David I. Stern, *Aggregation and the Role of Energy in the Economy*, Ecological Economics, **32**, (2000) 301-317.

3. J.H. Walsh, *2001 Carbon Dioxide Fact Sheet*, Web: pages.ca.inter.net/~jhwalsh/wfsesr.html.

4. N. Nakicenovic, Arnulf Grübler and Alan McDonald, *Global Energy Perspectives*, International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), Cambridge University Press, 1998. ISBN 0 521 64200 0.

5. J.H. Walsh, *World Per Capita Oil Consumption 1965-2001*, July 2002. Web: pages.ca.inter.net/~jhwalsh/oilcap.html.

December 2002

19 Lambton Avenue,
Ottawa, Ontario, K1M 0Z6
E-Mail: jhwalsh@ca.inter.net
(613) 745-6279
Web Site: pages.ca.inter.net/~jhwalsh/index.html