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Calculating economy-wide energy intensity decline rate: The role of sectoral output and energy shares

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Abstract

We specify formulas for computing the rate of decline in economy-wide energy intensity by aggregating its two determinants—technical efficiency improvements in the various sectors of the economy, and shifts in economic activity among these sectors. The formulas incorporate the interdependence between sectoral shares, and establish a one-to-one relation between sectoral output and energy shares. This helps to eliminate future energy intensity decline scenarios which involve implausible values of either sectoral share. An illustrative application of the formulas is provided, using within-sector efficiency improvement estimates suggested by Lightfoot–Green and Harvey.

Keywords: Energy intensity decline; Energy efficiency improvement; Sectoral change

1. Introduction

One measure of the role of energy, and the efficiency with which it is used, is energy intensity, the ratio of energy used per unit (real dollar) of output. Energy intensity can be measured at the individual industry or activity level, at a regional or national level, or on a global average basis. The International Energy Agency, and the United States' Energy Information Administration (EIA) gather data that can be used to calculate energy intensity on a variety of bases.

Smil (2003) demonstrates that the reliability of energy intensity ratios are in doubt, particularly because of measurement errors and differences in the ways in which energy on the one hand, and output on the other, are accounted for. An illustrative example is Smil's (2003, p. 75) demonstration that large intercountry differences in energy intensity almost disappear when output is measured on a purchasing-power-parity basis rather than using the market exchange rate. While these difficulties with the energy intensity concept, and measures of it, must be kept in mind, this paper focuses on first differences (changes over time) in energy intensity. As long as there is some time consistency in the measurement of energy and output, first differences should minimize any problem with using the concept of energy intensity.

Energy intensity, and its rate of change over time, occupies a central role in the climate change debate. It is increasingly widely understood that anthropogenically induced climate change is essentially an energy problem. The combustion of fossil fuels for energy purposes is the chief source of carbon dioxide (CO_2) emissions, the main greenhouse gas. Thus the type of energy and its use and conversion efficiencies are important parts of the climate change picture.

To be more precise, future projections (scenarios) of greenhouse gas emissions depend not only on projections of population growth and economic (energy-using) activities per capita, but also on changes in energy intensity and the degree to which future energy sources are carbon (or emission)-free. The Kaya Identity (Kaya, 1989) makes this

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relationship clear:

$$C \equiv P \frac{Y}{P} \frac{E}{Y} \frac{C}{E}, \tag{1}$$

where C is the carbon emissions, P the population, Y the gross domestic product (GDP), and E the energy. Hoffert et al. (1998), for example, used the Kaya Identity to express global anthropogenic CO_2 emission in 1990 as follows: 5.3×10^9 persons $\times$ 4100\$ per person per year $\times$ 0.49 Watt year per \$ $\times$ 0.56 kg C per Watt year $\approx$ 6 GtC per year.

The energy intensity variable in the Kaya Identity is E/Y. Over time, energy intensity is expected to decline with energy-efficiency-increasing technological progress.[2] However, in rapidly industrializing countries E/Y may increase as economic activity shifts from lower (e.g. peasant agriculture, fishing and trading) to higher (e.g. steel and cement production, chemical and petroleum processing, and paper making) energy-intensive activities. But once industrialization is achieved, and high incomes result in increased demand for professional and commercial services and activities, there will be a shift toward less energy-intensive activities. The combination of (i) within-sector energy efficiency improvements, and (ii) sectoral shifts in economic activities, will determine the direction and magnitude of change in overall (i.e. aggregated across the different sectors of an economy) energy intensity, E/Y.[3] Here it becomes useful to convert the Kaya Identity to a rate of change over time form:

$$\dot{C} = \dot{P} + (\dot{Y/P}) + (\dot{E/Y}) + (\dot{C/E}), \tag{2}$$

where a dot over a variable denotes its rate of change over time, i.e., for any variable x, $\dot{x} \equiv \mathrm{d}(\ln x)/\mathrm{d}t$. On a global average basis, the annual rate of decline in energy intensity, $(\dot{E/Y})$, has been in the neighborhood of 1% on a market exchange rate basis (0.7% on a purchasing-power-parity basis) over the past century (Smil, 2003).[4] An important question is whether a 1% rate of decline in global average annual energy intensity can be improved upon over the course of the 21st century. Or, alternatively, will it become more difficult to maintain a 1% rate of decline, as the best improvements in energy efficiency, and the largest gains from sectoral output shifts, are "used up". That these are important questions for climate policy is indicated in the papers by Hoffert et al. (1998, 2002).

Hoffert et al. (1998) demonstrates that large amounts of carbon-free energy would be required to stabilize the atmospheric concentration of CO_2, even at a level double the pre-industrial one of approximately 275 ppmv. They show that, given population and output (GDP) per capita growth projections employed in the 1990s by the Intergovernmental Panel on Climate Change (IPCC, 2000), the amount of carbon-free energy required to stabilize the atmospheric concentration of CO_2 at 550 ppmv would be 37 TW (or 1165 EJ/yr).[5] But this estimate assumed that the global average annual rate of decline in energy intensity throughout the 21st century would be maintained at 1%. If, in contrast, the average annual rate of decline could be raised (falls) to 1.5 (0.8)%, the amount of carbon-emission-free power required for stabilization would be 19 (50) TW.[6]

Reducing uncertainty about the future rate of decline in energy intensity would reduce uncertainty about future carbon emissions, and the amount of carbon-free energy required for climate stabilization. This, however, first requires the correct calculation of the rate of decline in overall energy intensity. A primary purpose of this paper is to specify formulas for computing the rate of decline in overall energy intensity by appropriately aggregating its two determinants—technical efficiency improvements in different economic activities, and sectoral shifts between economic activities that have different energy intensities. An important feature of the formulas developed in this paper is that they establish a one-to-one relationship between sectoral output and energy shares by explicitly incorporating the interdependence between these sectoral shares. This, as is shown below, facilitates elimination of unrealistic energy intensity decline scenarios.

Our paper is related to the literature on the development of energy-efficiency-related indicators such as Index Decomposition Analysis (IDA) (see, e.g., Ang, 2004, 2006; Boyd and Roop, 2004; Ang and Zhang, 2000; Lermit and Jollands, 2001; United States' Department of Energy (US DOE), 1995, 2003). However, an important distinction between IDA and our paper is as follows. While the former seeks to decompose the change in total energy consumption over time into causal factors, we seek to aggregate the causal factors in order to compute the change in overall energy intensity over time. The difference in the two approaches is motivated by the different objectives that we seek to achieve. IDA seeks to isolate the impact of energy efficiency improvements on changes in energy consumption. Our paper seeks to develop formulas which help to predict overall energy intensity decline from realistic projections of sectoral energy efficiency improvements and output shifts.

The rest of this paper is organized as follows. In Section 2 we lay out formulas for measuring the overall rate of energy intensity decline by appropriately combining the sectoral improvements in energy efficiency. Then, in Section 3, we illustrate how the formulas can be used to identify implausible energy intensity decline scenarios, and

[2] Energy efficiency, the inverse of energy intensity, is defined as output per unit energy. It refers to improvements in fuel economy, power plant heat rates, building operations, industrial processes, etc. (Laitner, 2004).

[3] In this paper, we alternatively refer to technical or within-sector efficiency improvements as "energy efficiency improvements", and aggregate or economy-wide activity as "activity".

[4] Decarbonization of energy has reduced the global carbon intensity of energy, $(\dot{C/E})$, by about 0.3% on an average annual basis.

[5] 1 Terawatt (TW) $\approx$ 31.5 Exajoules (EJ) per year, is a measure of power (energy per unit of time).

[6] Current global energy use is almost 14 TW, about 2 TW of which is carbon emission-free. For an assessment of the potential contribution of conventional carbon-free energies over the 21st century, see Green et al. (2007).