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Energy Policy 35 (2007) 6457–6466

ENERGY POLICY

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

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Received 14 October 2006; accepted 13 August 2007

**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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doi:10.1016/j.enpol.2007.08.018

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: $5.3 \times 10^9$ 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).

thus reduce uncertainty about its future rate of decline. In order to do this, we use the potential sectoral energy efficiency improvements estimated by Lightfoot and Green (2001), and the higher ones suggested by Harvey (2003). Concluding comments are provided in Section 4.

## 2. Calculating the overall energy intensity decline rate

In this section we first outline the Divisia Index approach to IDA, and then present our formulas for calculating the reduction in overall (i.e. economy-wide) energy intensity. IDA uses the theory of index numbers to decompose changes in energy consumption over time into various effects. The exact decomposition formula prescribed depends on the specific index number theory (such as Laspeyers, Paasche, Fisher, and Divisia) utilized. Amongst the various approaches to IDA, the Fisher Ideal Index approach and the Logarithmic Mean Divisia Index approach are preferable as they lead to consistency in aggregation (Boyd and Roop, 2004; Ang, 2006).

### 2.1. The Divisia Index approach: decomposition formulas

Consider an economy divided into $n$ sectors.[7,8] Let $e_i^0$ and $y_i^0$ respectively denote the energy used, and output (or GDP) generated, by sector $i$ in the base or "initial" year. Superscript $T$ is used to denote the value of the variables in the future or "final" year (the final year is $T$ years ahead of the base year). For instance, $y_i^T$ denotes the amount of output generated (at base year prices) by sector $i$ in the final year. The energy share and output share of sector $i$ in year $j$ are respectively given as $e_i^j/E^j \equiv w_i^j$ and $y_i^j/Y^j \equiv S_i^j$, where $E^j = \sum_{i=1}^n e_i^j$ and $Y^j = \sum_{i=1}^n y_i^j$ are total energy and output in year $j$ (with $j = 0, T$). Energy intensity of sector $i$ in year $j$ is denoted by $I_i^j \equiv e_i^j/y_i^j$.

The Divisia Index approach (see e.g. US DOE, 2003) decomposes the logarithmic change in total energy consumption over a period of time into three effects: activity effect, structural effect, and intensity effect. Using notations as defined above,[9] the amount of energy used at any instant of time can be expressed as

$$E \equiv \sum_i YS_iI_i. \tag{3}$$

In rate of change over time form, we can rewrite the above as

$$\dot{E} = \sum_i w_i\left[\dot{Y} + \dot{S}_i + \dot{I}_i\right], \tag{4}$$

where a dot over a variable denotes its rate of change over time. While (4) holds instantaneously, integrating both sides with respect to time over the interval 0–$T$ yields

$$\ln(E^T/E^0) = \sum_i w_i^* \ln(Y^T/Y^0) + \sum_i w_i^* \ln(S_i^T/S_i^0) + \sum_i w_i^* \ln(I_i^T/I_i^0). \tag{5}$$

Thus, the logarithmic change in total energy consumption between years 0 and $T$ (the left-hand side of Eq. (5)), can be expressed as a sum of three effects. The three terms on the right-hand side of (5) correspond respectively to activity effect, structural effect, and intensity effect. The weight $w_i^*$ of sector $i$ is derived by an averaging of the initial and final year energy share of sector $i$. The averaging process used depends on the assumption made about the rate of growth of the relevant variables between the initial and terminal time. While the Arithmetic Mean Divisia Index uses a simple average of the weights (i.e. $w_i^* = \frac{1}{2}(w_i^0 + w_i^T)$), the Logarithmic Mean Divisia Index uses a logarithmic average of the weights (i.e. $w_i^* = L(w_i^0, w_i^T)/\sum_i L(w_i^0, w_i^T)$, where $L(w_i^0, w_i^T) \equiv (w_i^T - w_i^0)/\ln(w_i^T/w_i^0)$).

As seen from the decomposition given by (5), changes in economy-wide energy consumption can arise due to three factors: (i) changes in aggregate activity level (the activity effect), (ii) changes in the relative size of the various sectors (the structural effect), and (iii) changes in the technical efficiency with which energy is used (the intensity effect). As the first two factors are unrelated to technical efficiency improvements, a primary objective of IDA is to separately estimate the impact of the third factor on changes in energy consumption.

### 2.2. An alternative approach: aggregation formulas

While isolating the effect of technical efficiency improvements on energy consumption is important, it is not the purpose of the present paper. Since we are mainly interested in reducing uncertainty about the future rate of decline in economy-wide energy intensity (arising as a result of any or all causal factors/effects), we do not seek to separate out the impact of a particular factor. Instead we do the opposite: we sum up the impacts of the various underlying factors in order to compute the change in economy-wide energy intensity over time.

The formula we use to compute the reduction in overall energy intensity is derived as follows. Denote the percentage decline in energy intensity for the entire economy over the period spanning the initial and the final year by $R$, i.e., $R = ((E^0/Y^0) - (E^T/Y^T))/(E^0/Y^0)$. Let $\alpha$ denote the average annual rate of decline in economy-wide energy intensity over these $T$ years, i.e., $E^T/Y^T = (E^0/Y^0)(1-\alpha)^T$. Then, we have

$$\alpha = 1 - (1 - R)^{1/T}. \tag{6}$$

A decline in the economy-wide energy intensity level can be caused by (i) improvements in energy efficiency in the

[7] The analysis that follows can be generalized to incorporate sub-sectors within a sector.

[8] For example, for calculating its energy intensity indicators, the United States' Department of Energy divides the US economy into five broad sectors: Residential, Commercial, Industrial, Transportation, and Electric Power.

[9] The instantaneous values of the variables appear without the time superscript.

various sectors of the economy ("technological change"), and (ii) sectoral shifts in economic activities that have differing energy intensities ("structural change"). These sectoral changes, and the resultant overall energy intensity decline, can arise due to both autonomous energy efficiency increases (AEEI) as well as price-induced changes. Appropriate summation of the causal factors, in order to derive the economy-wide energy intensity decline rate, is carried out as follows:

$$1 - R = \frac{E^T/Y^T}{E^0/Y^0} = \frac{Y^0}{E^0 Y^T}\sum_i e_i^T = \sum_i \frac{Y^0 e_i^T}{E^0 Y^T} = \sum_i \left\{ \frac{e_i^0}{E^0}\frac{y_i^0/e_i^0}{y_i^T/e_i^T}\frac{y_i^T/Y^T}{y_i^0/Y^0} \right\} = \sum_i \left\{ w_i^0 \frac{I_i^T}{I_i^0}\frac{S_i^T}{S_i^0} \right\}, \qquad (7)$$

where the fourth equality in (7) follows from cancellation of the common terms in the numerator and denominator (i.e. $e_i^0$, $y_i^0$, and $y_i^T$), and the last equality follows from the definitions of $w_i^0$, $I_i^0$, $I_i^T$, $S_i^0$, and $S_i^T$.

Eqs. (6) and (7) show that to calculate the average rate of energy intensity decline for the entire economy, we need information on (i) the initial year energy share of each sector, $w_i^0$, (ii) the improvement in energy efficiency of each sector, $I_i^0/I_i^T = (y_i^T/e_i^T)/(y_i^0/e_i^0)$, and (iii) the ratio of final-to-initial year output share of each sector, $S_i^T/S_i^0$.[10] Moreover, given these three pieces of information, the final year energy share of each sector, $w_i^T$, can also be derived by using the following formula:

$$w_i^T = \frac{e_i^T}{\sum_i e_i^T} = \frac{(e_i^T Y^0)/(E^0 Y^T)}{\sum_i (e_i^T Y^0)/(E^0 Y^T)} = \frac{(w_i^0 S_i^T I_i^T)/(S_i^0 I_i^0)}{\sum_i (w_i^0 S_i^T I_i^T)/(S_i^0 I_i^0)} = \frac{(w_i^0 S_i^T I_i^T)/(S_i^0 I_i^0)}{1-R}. \qquad (8)$$

In Eq. (8), the second equality follows from cancellation of the common terms (i.e. $E^0$, $Y^0$, and $Y^T$) in the numerator and denominator; the third equality comes from the definitions of $w_i^0$, $I_i^0$, $I_i^T$, $S_i^0$, $S_i^T$; and the last equality is obtained using (7).

Appendix A provides alternative aggregation formulas which require different information about the initial and final years than those required for (7) and (8). One implication that emerges from (8) is that constant sectoral output shares over time (i.e. $S_i^0 = S_i^T$) do not, in general, imply constant sectoral energy shares over time (i.e. $w_i^0 \neq w_i^T$), and vice versa. The exception to this is the highly unlikely case when energy efficiency improvements, $I_i^T/I_i^0$, are identical across all sectors, in which case $S_i^0 = S_i^T \Leftrightarrow w_i^0 = w_i^T$.

Note that GDP-generating activities can be measured in physical units (such as floor space, passenger miles, ton miles, or kWh), or in value terms (constant dollars). In this paper we take the latter approach, i.e., we measure activities within each sector in terms of their contribution ($y_i$) to GDP. This not only facilitates aggregation of activities across sectors, but also provides us with a measure of energy intensity (the "energy–GDP ratio") that is most appropriate for use with the Kaya Identity.

## 3. Future energy intensity decline scenarios

The formulas developed in the previous section can aid in the construction of "realistic" greenhouse gas emission scenarios, such as those produced by the IPCC (2000). These scenarios themselves depend on what rates of future energy intensity decline one considers plausible.[11] Eq. (7) shows that the future rate of energy intensity decline can be estimated using, inter alia, predictions about future output shares ($S_i^T$). Because Eq. (8) establishes a one-to-one relationship between future output and energy shares of each sector, this equation can help to eliminate scenarios involving "unrealistic" values for either sectoral share.

Suppose, without loss of generality, the "initial year" is 1990 while the "final year" is 2100. Given known sectoral energy and output shares in the initial year ($w_i^0$ and $S_i^0$), and projected improvement in energy efficiency of each sector ($I_i^0/I_i^T$) over the 110 years (1990–2100), Eq. (7) shows that the extent of economy-wide energy intensity decline ($R$) over the same period will depend on the final year output share ($S_i^T$) of each sector. Suppose a particular scenario predicts (or assumes) that the future sectoral output shares will take the values $\hat{S}_i^T$ (for $i = 1, 2, \ldots, n$), and computes, using (7), the resultant economy-wide energy intensity decline to be $\hat{R}$. Call this the first step. In the second step, using (8), we can also compute the corresponding sectoral energy shares in 2100 (denote these latter values as $\hat{w}_i^T$). If these sectoral energy shares $\hat{w}_i^T$ that emerge are deemed to be implausible, then this will call into question the reasonableness of the assumed output shares $\hat{S}_i^T$, and the computed (in the first step) $\hat{R}$.

In other words, since the economy-wide energy intensity decline rate can be computed using future sectoral output shares in (7), there is a possibility of deriving unrealistic values of $R$ by using $S_i^T$ values which may seem *per se* reasonable, but yield unreasonable $w_i^T$ values. By capturing the interdependence between the variables, Eq. (8) thus provides a reality check for the projections used in Eq. (7).

Since the sectoral shares of energy, as well as output, must add up to one (i.e. 100%), our formulas therefore compute overall energy intensity decline in a "general-equilibrium" rather than a "partial-equilibrium" framework. For instance, (7) and (8) reveal that a constant-sum reallocation of future output share between any two sectors leads to different future energy shares for *all* the sectors. Predicting future energy intensity decline in a partial-equilibrium framework (i.e. analyzing a few sectors of the economy at a time in isolation) thus misses out the

[10] Suppose the "initial" year is 1990 and the "final" year is 2100. Then the first information can be obtained from historical data, while the last two will involve future projections.

[11] In IPCC's 40 SRES scenarios, global average annual rate of energy intensity decline over 1990–2100 ranges from 0.57% to 2.18%, three-quarters of these being 1.1% or higher.

Table 1
Global energy intensity decline estimate

| 1<br>Sector | 2<br>Primary energy share in 1990[a]<br>$(w_i^0)$ | 3<br>Energy efficiency improvement (1990–2100)[b]<br>$\left(\frac{y_i^T/e_i^T}{y_i^0/e_i^0}-1\right)$ | 4<br>Output share in 1990[c]<br>$(S_i^0)$ | 5<br>Output share in 2100[d]<br>$(S_i^T)$ | 6<br>Implied primary energy share in 2100[e]<br>$(w_i^T)$ |
|---|---|---|---|---|---|
| Electricity generation | 37.5 | 85 | 4 | 3 | 47.5 |
| Transportation | 18.6 | 200 | 6 | 7 | 22.6 |
| Residential | 12.1 | 300 | 5 | 3 | 5.7 |
| Industrial—high | 16.9[f] | 200 | 10 | 4 | 7 |
| Industrial—low | 5.0[f] | 200 | 26 | 28 | 5.6 |
| Commercial | 9.9 | 200 | 49 | 55 | 11.6 |
| Total | 100 | | 100 | 100 | 100 |

All figures in %.
[a]Computed by Lightfoot and Green (2001) using US EIA data.
[b]Estimated by Lightfoot and Green (2001).
[c]Computed by authors using World Bank (2000) data. Suitable adjustments have been made to match the EIA's energy sectors with the World Bank's output sectors (see Appendix C).
[d]Assumed or predicted.
[e]Calculated using Eq. (8).
[f]Calculated by authors using estimates that (i) the average energy intensity in the "Industrial—High" sub-sector is 8.75 times the average energy intensity of the "Industrial—Low" sub-sector (Miketa, 2001), and (ii) the "Industrial—High" sub-sector accounts for 10/36 ($\approx$28%) of global output generated by the Industrial sector (see Appendix C).

interdependence between the output and energy shares of the various sectors, and is likely to give erroneous results.

### 3.1. An illustrative example

To illustrate the above point, we use the Lightfoot and Green (2001) estimates for maximum attainable improvements in energy efficiency for different energy-using sectors.[12] Improvements in energy efficiency are limited by physical and thermodynamic constraints in Lightfoot and Green (2001) and Lightfoot (2007). Following them, we assume that the maximum attainable improvements are achieved by the year 2100.

The data needed to estimate the global average rate of energy intensity decline are presented in Table 1. Following United States' Department of Energy, we divide the global economy into five broad sectors—Electricity generation, Transportation, Residential, Industrial, and Commercial. Moreover, we divide the Industrial sector into two sub-sectors—one representing industries with high energy intensity ("Industrial—High"), and the other representing those with low energy intensity ("Industrial—Low").[13] The table shows, respectively, the 1990 energy and output shares in columns 2 and 4, the Lightfoot–Green technical efficiency improvements in column 3,[14] and the assumed 2100 output shares in column 5. The sectoral energy shares refer to quantity shares of primary energy. Combined, using Eqs. (6) and (7), the information in columns 2–5 in Table 1 gives a final-to-initial energy intensity ratio $(E^T/Y^T)/(E^0/Y^0)=0.32$, and a global average annual rate of energy intensity decline of 1.03%.[15] The implied sectoral energy shares in 2100, calculated using Eq. (8), are reported in column 6. The future output and energy shares in Table 1 seem plausible in our judgment.

[12]Thus the Lightfoot–Green estimates are used for the purpose of illustration only. Note that our formulas (7) and (8) are general in nature. They can be used with alternative (better) data sets in order to check whether future energy intensity decline scenarios involve realistic projections of sectoral output *and* energy shares.

[13]Five industry groups—ferrous metals (iron and steel), non-ferrous metals (e.g. zinc, copper), non-metallic minerals (e.g. cement, glass), pulp and paper, and chemicals and petrochemicals—have energy intensities which, on average, are 8.75 times higher than the energy intensities of the other industry groups (Miketa, 2001, Table 1). These five industries are included in our "Industrial—High" sub-sector, while the remaining are under "Industrial—Low". We sub-divide the Industrial sector in order to deal with the widely held view that, over the course of the 21st century, industrial output will shift away from the more energy-intensive industries to the less energy-intensive ones.

[14]Note that a sectoral energy efficiency increase of 200% (respectively, 300%) over the 110-year period implies an energy efficiency increase at the rate of 1% (respectively 1.27%) per year. This increase includes both AEEI as well as price-induced changes. Bataille et al. (2006, p. 106) report an AEEI of 0.25–0.5% (respectively, 0.75–1.5%) for top-down (respectively, bottom-up) energy-economy models. Their Table 5 provides sectoral AEEIs for Canada for 2000–2035.

[15]Given any ratio of final year to initial year energy intensity, the average annual rate of decline in energy intensity depends on the number of years involved. Note that, following Lightfoot and Green (2001), we have assumed that their maximum attainable energy efficiency improvements are achieved by 2100, which gives us 110 years from 1990. This also facilitates comparison with IPCC (2000).

Table 2
Sensitivity analyses: likely (A, B, and C) and unlikely (D, F, and G) scenarios

| Sector | Primary energy share in 1990 ($w_i^0$) | Energy efficiency improvement (1990–2100) $\left(\frac{y_i^T/e_i^T}{y_i^0/e_i^0}-1\right)$ | Output share in 1990 ($S_i^0$) | GDP share, $S_i^T$ (implied primary energy share, $w_i^T$) in 2100 Scenarios: A | B | C | D | F | G |
|---|---|---|---|---|---|---|---|---|---|
| Electricity generation | 37.5 | 85 | 4 | 3 (41.7) | 2.7 (45) | 2 (39) | 6 (56.9) | 1 (21.6) | 0.1 (2.2) |
| Transportation | 18.6 | 200 | 6 | 10 (28.3) | 5.3 (18) | 7 (27.8) | 10 (19.3) | 7 (30.8) | 9 (41.2) |
| Residential | 12.1 | 300 | 5 | 4 (6.6) | 4 (8) | 3 (7) | 5 (5.7) | 3 (7.7) | 6 (16.1) |
| Industrial—high | 16.9 | 200 | 10 | 6 (9.3) | 6 (11.1) | 2 (4.3) | 9 (9.5) | 7 (16.8) | 7 (17.5) |
| Industrial—low | 5.0 | 200 | 26 | 19 (3.3) | 20 (4.2) | 28 (6.9) | 27 (3.2) | 25 (6.8) | 23 (6.5) |
| Commercial | 9.9 | 200 | 49 | 58 (10.7) | 62 (13.7) | 58 (15) | 43 (5.4) | 57 (16.3) | 54.9 (16.4) |
| Total | 100 | | 100 | 100 (100) | 100 (100) | 100 (100) | 100 (100) | 100 (100) | 100 (100) |
| Energy intensity ratio, $(E^T/Y^T)/(E^0/Y^0)$ | | | | *0.36* | *0.3* | *0.26* | *0.535* | *0.235* | *0.226* |
| *Average annual rate of energy intensity decline, 1990–2100* | | | | *0.91* | *1.08* | *1.22* | *0.57* | *1.31* | *1.34* |

All numbers in percentage.

### 3.2. Sensitivity analyses

To analyze the sensitivity of the global energy intensity decline rate to different assumptions of future output (and the associated energy) shares, we report some other scenarios in Table 2. We are mainly interested in more "likely" cases, the ones in which the energy share of the electricity generation sector rises from 37.5% in the 1990s to 40–50% by 2100;[16] the transportation energy share moves between 15% and 30% (its current share is 18.6%); industrial output shifts away from the more energy-intensive industries; and the large, hypothesized decline in the energy and output shares of the industrial sector is, at least partly, taken up in energy and output shares of the commercial sector. We are particularly concerned to capture the predicted and ongoing rise in the output share of the commercial sector (which includes retail and wholesale trade, and professional services such as health, education, finance, and real estate). The output share of the commercial sector has been growing rapidly in developed countries, and can be expected to grow worldwide as developing countries become developed.

Scenarios A, B, and C in Table 2, which involve plausible assumptions about the future sectoral shares, yield an average annual rate of energy intensity decline of 0.91%, 1.08%, and 1.22%, respectively. On the other hand, the energy intensity decline rate for scenarios D, F, and G are, respectively, 0.57%, 1.31%, and 1.34%. Scenarios D, F, and G are, however, associated with unlikely future sectoral shares. In scenario D, the future output share of the commercial sector is too low, while the future output share of the industrial sector seems high. In scenarios F and G, energy share of the electricity generation sector are too low (see footnote 16).

Although not reported here, we constructed many other scenarios in our preliminary research using various other combinations of future sectoral shares.[17] For all the "likely" scenarios, the global average rate of energy intensity decline ranged between 0.9% and 1.2% per annum. This raises questions about the appropriateness of the (often implicit) assumptions about intersectoral shares made by those who suggest a much larger (2–3% per annum) rate of decline in overall energy intensity over the course of the 21st century (see, e.g., Laitner, 2004).

Some have criticized the Lightfoot–Green energy efficiency improvement estimates as being on the conservative side, as these only take into account "device", but not "systems", efficiencies. Harvey (2003), for example, has conjectured that the energy efficiency of buildings (systems) could be raised as much as 600% (which is much higher than the 300% figure that Lightfoot and Green used for the residential sector), by combining architectural innovations and advanced building materials in such a way that most energy requirements for space heating, cooling, air filtering, and lighting would be obviated. Although it is questionable whether systems efficiencies would allow, on a global average scale, energy efficiency increases that are much larger than the ones employed by Lightfoot and Green, it is interesting to investigate the implications of very large

[16] The role of electricity in the energy mix has been growing over time (US DOE, 1995, p. 47). Smil (2003, p. 365) also argues that with a third of the world still not on the electrical grid, the relative importance of the electricity generation sector is virtually certain to grow.

[17] These scenarios are available upon request from the authors.

Table 3
Sensitivity analysis: very large energy efficiency improvements in downstream end-use sectors (all figures in percentage)

| 1<br>Sector | 2<br>Primary energy share in 1990<br>$(w_i^0)$ | 3<br>Energy efficiency improvement (1990–2100)<br>$\left(\frac{y_i^T/e_i^T}{y_i^0/e_i^0}-1\right)$ | 4<br>Output share in 1990<br>$(S_i^0)$ | 5<br>Output share in 2100<br>$(S_i^T)$ | 6<br>Implied primary energy share in 2100<br>$(w_i^T)$ |
|---|---|---|---|---|---|
| Electricity generation | 37.5 | 85 | 4 | 3 | 60.7 |
| Transportation | 18.6 | 400 | 6 | 7 | 17.3 |
| Residential | 12.1 | 600 | 5 | 3 | 4.8 |
| Industrial—high | 16.9 | 400 | 10 | 4 | 5.4 |
| Industrial—low | 5.0 | 400 | 26 | 28 | 4.3 |
| Commercial | 9.9 | 600 | 49 | 55 | 7.4 |
| Total | 100 | | 100 | 100 | 100 |

Energy intensity ratio, $(E^T/Y^T)/(E^0/Y^0) = 0.25$.
Average rate of overall energy intensity decline (1990–2100) = 1.25% per annum.

energy efficiency increases in the downstream end-use sectors (i.e. transportation, residential, industrial, and commercial).[18]

Table 3 modifies the energy efficiency improvement numbers used in Table 1 for the downstream end-use sectors. Specifically, in Table 3, we assume that energy efficiency in the residential and commercial sectors increases by 600% (instead of 300% and 200%, respectively, in Table 1), while that in the transportation and industrial sectors increases by 400% (instead of 200%). Surprisingly, even these large increases in sectoral energy efficiency improvements raise the overall energy intensity decline rate by a modest amount—from 1.03% to 1.25% per annum.

A question that arises then is as follows. Given the (plausible) energy and output shares in Table 1, what is the amount by which technical efficiency must improve at the sectoral level in order to bring about a 2% per annum decline in global energy intensity over 1990–2100? Appendix B addresses this question, specifies a formula that can be used to deal with such questions in general, and demonstrates that energy efficiency improvements would have to range up to 1000%.

## 4. Conclusion

The paper develops formulas for computing the economy-wide weighted average energy intensity decline associated with estimates of sectoral energy efficiency improvements and shifts in sectoral output shares. Section 2 shows that in order to compute the rate of decline in overall energy intensity for a specified period of time, we need information about (i) initial year energy share of each sector, (ii) the energy efficiency improvements in each sector, and (iii) the ratio of final year to initial year output share of each sector. When the formulas in Section 2 are used to estimate the future rate of decline in overall energy intensity, then the one-to-one correspondence between the future output and energy shares can be used to eliminate scenarios involving unlikely values for either sectoral shares. By explicitly capturing the linkages between output and energy shares of the various sectors, Eq. (8) provides additional basis and structure for the construction of realistic energy intensity decline scenarios.

Section 3 uses the Lightfoot–Green (2001) estimates of future energy efficiency increases in order to illustrate how the formulas in Section 2 might be used. If these estimates of maximum attainable energy efficiency improvements are correct, then the global average energy intensity decline will likely fall somewhere in the range of 0.9–1.2% per annum over the course of the 21st century. This range for $E/Y$ appears consistent with recent estimates of the rates of decline in global carbon intensity of output, over 2000–2100, contained in Weyant et al. (2006).[19]

## Acknowledgments

We thank Peter Green, Ngo Van Long, and two anonymous referees of this journal for helpful comments and suggestions. All remaining errors are our responsibility.

[18] As noted by Lightfoot and Green (2001, p. 12), "although major reductions in energy intensity are possible in transportation, residential, industrial, and commercial, there are limits on improvement in energy efficiency for electricity generation, a sector which is likely to increase in relative importance and limit the overall world energy intensity decline." Scope for efficiency improvements in the electricity generation sector is limited due to the state of current technology in this sector.

[19] The annual rate of decline in global carbon intensity of output (i.e. $C/Y$) ranges from 0.44% to 2.09% in Weyant et al. (2006, Tables 5 and 16), with a mean reference decline of 1.08%. Note that, similar to Eq. (2), we have $(C/Y) = (E/Y) + (C/E)$. Also see footnote 4.

## Appendix A. Alternative formulas for computing economy-wide energy intensity decline rate

In contrast to Eq. (7), an alternative formula can be used to combine technological change and structural change in order to obtain the economy-wide decline in energy intensity, $R$:

$$\frac{1}{1-R}=\frac{E^0/Y^0}{E^T/Y^T}=\sum_i\left\{\frac{y_i^0}{Y^0}\frac{y_i^T/e_i^T}{y_i^0/e_i^0}\frac{e_i^T/E^T}{e_i^0/E^0}\right\}=\sum_i\left\{S_i^0\frac{I_i^0}{I_i^T}\frac{w_i^T}{w_i^0}\right\}. \quad (A.1)$$

Eq. (A.1) shows that an alternative information set can be used to calculate the energy intensity decline for the entire economy: (i) the initial year output share of each sector, $S_i^0$, (ii) the energy efficiency improvement of each sector, $I_i^0/I_i^T=(y_i^T/e_i^T)/(y_i^0/e_i^0)$, and (iii) the ratio of final-to-initial year energy share of each sector, $w_i^T/w_i^0$. Furthermore, given this alternative information set, the final year output share of each sector can then be obtained as

$$S_i^T=\frac{y_i^T}{\sum_i y_i^T}=\frac{(y_i^T E^0)/(Y^0E^T)}{\sum_i(y_i^T E^0)/(Y^0E^T)}=\frac{w_i^T S_i^0 I_i^0/w_i^0 I_i^T}{\sum_i w_i^T S_i^0 I_i^0/w_i^0 I_i^T}=\frac{w_i^T S_i^0 I_i^0/w_i^0 I_i^T}{1/(1-R)}. \quad (A.2)$$

The formulas in (A.1) and (A.2) are analogous to the ones given in (7) and (8), and can be used in a similar manner to identify plausible energy intensity decline scenarios.

## Appendix B. Technical efficiency improvements necessary for a specified decline in economy-wide energy intensity

Suppose we have information on energy and output shares of each sector for both the initial and the final year, i.e., $w_i^0$, $w_i^T$, $S_i^0$, $S_i^T$. What is the amount by which energy efficiency of each sector would have to improve between the initial and the final years, in order to bring about an $R$ percent (where $R$ is some specified number) decline in economy-wide energy intensity? The sectoral energy efficiency improvements necessary for this purpose can be derived as follows:

$$\frac{y_i^T/e_i^T}{y_i^0/e_i^0}=\frac{(E^T y_i^T)/(e_i^T Y^T)}{(E^0 y_i^0)/(e_i^0 Y^0)}\frac{E^0/Y^0}{E^T/Y^T}=\frac{S_i^T/w_i^T}{S_i^0/w_i^0}\frac{1}{(1-R)}. \quad (B.1)$$

Different values of $w_i^0$, $w_i^T$, $S_i^0$, $S_i^T$ and $R$ will yield different values of $(y_i^T/e_i^T)/(y_i^0/e_i^0)$, as shown by (B.1).

Table 4 provides an illustrative example. Suppose sectoral shares of energy and output in 1990 and 2100 are as given in columns 2–5 (same values as those in Table 1). The 1990 data are historical, while the 2100 data are predicted values. Also, suppose global energy intensity has to decline at an average annual rate of 2% over the 110-year period. This implies $1-R=(E^T/Y^T)/(E^0/Y^0)=0.108$. The sectoral energy efficiency improvements which would bring this about are computed using (B.1) and given in column 6. The numbers in column 6 provide an idea as to how much technology must improve in each sector in order to achieve the 2% decline in global energy intensity. These numbers seem unrealistically large to us (especially for the electricity generation sector), and are likely to be unachievable due to physical and thermodynamic constraints pointed out by Lightfoot and Green (2001) and Lightfoot (2007).

## Appendix C. 1990 GDP shares for the energy end-use sectors

Global data for sectoral GDP shares are supplied by the World Bank (2000) and is available in their World Development Report. Sectoral GDP share data, by country and for the world, are broken into three broad groups: agriculture, industrial, and services. Data are also supplied for manufacturing—the main sub-sector in the "industrial" group. The three broad sectors include the following: "agriculture" also includes forestry and fishing; "industrial" includes, in addition to manufacturing,

Table 4
Technical efficiency improvements necessary for a 2% average annual rate of global energy intensity decline over 1990–2100 (all figures in %)

| 1<br>Sector | 2<br>Primary energy share in 1990<br>($w_i^0$) | 3<br>Output share in 1990<br>($S_i^0$) | 4<br>Primary energy share in 2100<br>($w_i^T$) | 5<br>Output share in 2100<br>($S_i^T$) | 6<br>Required sectoral energy efficiency improvement<br>$\left(\frac{y_i^T/e_i^T}{y_i^0/e_i^0}-1\right)$ |
|---|---|---|---|---|---|
| Electricity generation | 37.5 | 4 | 47.5 | 3 | 446.4 |
| Transportation | 18.6 | 6 | 22.6 | 7 | 786 |
| Residential | 12.1 | 4 | 5.7 | 3 | 1081.3 |
| Industrial—high | 16.9 | 12 | 7 | 4 | 786 |
| Industrial—low | 5 | 24 | 5.6 | 28 | 786 |
| Commercial | 9.9 | 49 | 11.6 | 55 | 786 |
| Total | 100 | 100 | 100 | 100 | |

Table 5
1990 GDP shares for the energy end-use sectors

| World Bank GDP share (1990) | EIA energy groups | GDP Shares corresponding to EIA energy share group |
|---|---|---|
| Industrial (34%): Electricity (4%), gas, water supply | Electricity generation | 4% [a] |
| Agriculture (including forestry, fishing) (6%); Industrial (34%): Manufacturing, Mining, Construction | Industrial | 36% [b] |
| Services (60%): Transportation service | Transportation | 6% [c] |
| Services (60%): Household services (5%) | Residential | 5% [c] |
| Services (60%): Retail and wholesale trade, Personal and professional, Finance, insurance and real estate | Commercial | 49% [d] |
| | | 100% |

[a] The electricity generation share of GDP was calculated using World Bank data on kWh per capita and population (in 1990) and an assumed price of 10 c per kWh. A further assumption is that the value added of the electricity generation sector is 80% of the revenue it generated.
[b] 34% (World Bank "industrial" + 6% agriculture -4% electricity generation = 36%.
[c] Because global output shares for transportation and household (residential) GDP are lacking, we used Canadian data for the former and US data for the latter.
[d] 60% (World Bank "services") -6% (transportation) -5% (residential) = 49%.

mining, construction, and electricity, gas and water supply. ''Services'' is all the rest, including retail and wholesale trade, transportation services, housing services, personal and professional services, financial services along with insurance and real estate, and government (all levels).

The World Bank output sectors are defined differently from the US EIA's energy sectors. Output shares are needed for the following energy end-use sectors: electricity generation, transportation, residential, industrial, and commercial. To match the sectoral output and energy shares required us to make two main adjustments. First, we pulled electricity supply out from the industrial output group, while subsuming agriculture, forestry, and fishing in the industrial energy group. Second, we pulled transportation and household services out of the output ''services'' group. Table 5 illustrates.

Five major industry groups (ferrous metals, non-ferrous metals, non-metallic minerals, pulp and paper, and chemicals and petrochemicals), accounting for *a third* of manufacturing GDP, have energy intensities that, on average, are 8.75 times greater than the average energy intensity of the other industry groups (Miketa, 2001). Manufacturing accounted for 22% of global GDP in 1990, and is a major component of the 36% of GDP, in 1990, accounted for by the World Bank's industrial sector. Of the remaining 14% (36% minus 22%) of output in the industrial sector, about 3% is generated by mining activities, including oil and gas wells. On the whole, mining is a very energy-intensive activity. Thus overall, we guesstimate that about 10% of all GDP is ''highly energy intensive''.

Since our initial year (1990) output share numbers for the different energy end-use sectors are approximations (recall footnote 12), we investigated the sensitivity of the overall energy intensity decline rate to variations in initial year output shares, and found that the former is not very sensitive to the latter.

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