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Industry-level Total-factor Energy Efficiency in Developed Countries

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Satoshi Honma[*], Jin-Li Hu[†]

Abstract

This study computes and analyzes the total-factor energy efficiency (TFEE) of 11 industries in 14 developed countries during the period of 1995-2005 using the data envelopment analysis (DEA) approach. There are four inputs: labor, capital stock, intermediate inputs other than energy, and energy. The value added is the only output. The most inefficient industry is the metal industry, which has an average TFEE of 40.6%. Australia is the most inefficient country, with the lowest weighted TFEE in every year except for 1996 and 1998. The most efficient countries are the United States from 1995 to 1998, Denmark from 1999 to 2002, and Netherlands from 2003 to 2005. Given that the number of efficient industries decreases over time, it is clear that most industries have room to improve their energy efficiency as time goes by. Moreover, based on the total-factor framework, this study finds no support for the convergence of energy efficiency levels.

Keywords: Data envelopment analysis (DEA); Total-factor energy efficiency; Industry-level analysis

JEL classification codes: Q40; Q30; Q32

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1. Introduction

Saving energy consumption is a top-priority concern in the environmental field from the viewpoint of both resource conservation and efforts to combat global warming. In general, it is not satisfactory to accept that declining economic growth is a consequence of reducing energy consumption. Therefore, setting energy efficiency targets without negatively affecting economic performance is an important issue for every economy.

Major developed countries have implemented various policies to improve energy efficiency since the first oil crises in 1973 (Geller et al., 2006). Recently the European Council advocated the ambitious targets, so-called as 20/20/20 goals (Council of European Union, 2007):

- Reduce greenhouse gas (GHG) emissions by 20% in 2020 compared to 1990 levels;
- Increase energy efficiency to save 20 % of EU energy consumption by 2020;
- Reach 20% of renewable energy in the total EU energy consumption by 2020.

Energy efficiency appears to be the only energy item in these fundamental EU goals: reduction of GHG emissions, improvement of energy stability, cutting energy costs, and enhancing economic competitiveness (European Communities, 2009). For these reasons, “energy efficiency can be seen as Europe’s biggest energy source” (European Commission, 2011). Note that not only does increasing energy efficiency can lead to reduce GHGs but also it can increase the renewable energy share without new investment (Harmsen et al., 2011). One of the key drivers to improve energy efficiency in industrial sector is technological change. It is critically affected by the political framework and stricter standard of carbon dioxide reduction (Blesl, et al., 2010). The importance of energy efficiency targets in policy-making processes cannot be emphasized enough.

The current EU's 20/20/20 policy may, however, be naïve and suboptimal. The uniform application of the common goals to all EU member states is neither fair nor equitable because energy efficiency varies across countries (Tolón-Becerra et al., 2010). Simulation in Capros et al. (2011) show that EU energy policy will causes undesirable distributional impact, and, therefore, that targets should be set with consideration for fairness. A country's energy consumption savings should be differentiated depending upon the current efficiency of each country.

In order to set well-designed energy efficiency targets, one should know disaggregated energy efficiency information. The traditional energy intensity indicator, which is defined as energy consumption per unit of GDP, has been used in formal statistics (EC, 2009). Most of the energy intensity studies show that energy intensity levels tend to be converged (Nilsson, 1993; Mielnik and Goldemberg, 2000; Sun, 2002; Alcantara and Duro, 2004; Markandya et al., 2006; Ezcurra, 2007; Liddle, 2010); however, others instead show the opposite results with diverging energy intensity levels (Mendiluce et al., 2010; Le Pen and Sévi, 2010).

Energy intensity and energy productivity, which is reciprocal of each other, have been used governmental programs and academic research. However, calculating the energy productivity ratio, which is defined as GDP divided by energy, may not always yield robust conclusions, as this method does not take into account that other inputs such as labor and capital can be substituted with energy (Wilson et al., 1994). As Patterson (1996) points out, the energy productivity ratio can be decreased simply by substituting energy for labor. Energy efficiency should therefore be evaluated using a multiple input-output model. The data envelopment analysis (DEA) approach, which is a non-parametric method of linear programming, is suitable for this purpose. We employ the total-factor energy efficiency (TFEE) concept that was advocated by Hu and Wang (2006) and is defined as the ratio of the target energy input, as suggested by the DEA, to the actual energy input. The TFEE index has been applied to the regional and national economies in China (Hu and Wang, 2006; Chang and Hu, 2010), Asia-Pacific Economic Cooperation (APEC) economies (Hu and Kao, 2007), Japan (Honma and Hu, 2008, 2009), and Taiwan (Hu et al., forthcoming).

Several studies (e.g., Hu and Kao (2007) and Zhou and Ang (2008)) have evaluated aggregated energy efficiency using the DEA approach. The former study measures energy efficiency for 17 APEC economies and the latter for 21 OECD countries. Moreover, Sözen and Alp (2009) use the DEA method to evaluate energy consumption, greenhouse gas emissions and local pollutants in Turkey, Switzerland, and 27 EU countries. Lozano and Gutiérrez (2008) propose three models for evaluating efficiency using population, GDP, energy consumption, and greenhouse gas emissions. They use these models to study 28 of the Annex B countries that were specified in the Kyoto Protocol.

Information regarding aggregate total-factor energy efficiency is useful but only provides a rough sketch of nationwide energy consumption. Countries have both efficient and inefficient industries, and aggregate efficiency scores cannot tell the government which industries need to improve in this regard. A more in-depth analysis requires disaggregate data regarding energy efficiency across countries. Previous studies of industry-level energy efficiency, however, have not incorporated cross-country comparisons into their analysis. Mukherjee (2008) uses DEA to measure the energy efficiency of the six sectors with the highest energy consumption in the United States. Honma and Hu (forthcoming) also measure TFEE in 17 industries in the Japanese economy. To the best of our knowledge, no study has measured economy-wide energy efficiency performance in specific industries using DEA. The reason for this is that — even for developed countries — no credible data regarding capital stock that are derived using a uniform method and are internationally compatible have been made available on the industry level. However, the EU-KLEMS (2008) project, which was financed by the European Commission, has developed a comprehensive database for developed countries that allows researchers to compare industry-level efficiency at the international level.

The purpose of the present study is to compute the TFEE of 11 industries in 14 developed countries for the period of 1995-2005. This is the first study of industry-level energy efficiency across developed countries.

We review the trends in energy efficiency both by industry and by country. Moreover, for each year, we determine the total potential energy savings for each country.

The remainder of the paper is organized as follows: Section 2 provides our methodology and data. Section 3 presents our empirical results and discussion. Finally, Section 4 concludes this paper.

2. Methodology and Data

2.1 DEA Methodology

DEA is a linear programming method that is used to assess the comparative efficiency of decision-making units (DMUs), such as countries, regions, firms, and other organizations. There are K inputs and M outputs for each of the N DMUs. The envelopment of the *i*-th DMU can be derived using the following linear programming problem under the assumption of variable returns to scale (VRS) proposed by Banker et al. (1984):

$$\begin{aligned} &\text{Min}_{\theta,\lambda} \quad \theta \\ &\text{s.t.} \quad -y_i + Y\lambda \geq 0 \\ &\theta x_i - X\lambda \geq 0 \\ &e\lambda = 1 \\ &\lambda \geq 0, \end{aligned} \tag{1}$$

where θ is a scalar that represents the efficiency score of the *i*-th DMU; e is an Nx1 vector of ones; λ is an Nx1 vector of constants; y_i is an M×1 output vector of DMU i; Y is an M×N output matrix composed of all output vectors of the N DMUs; x_i is a K×1 input vector of DMU i; and X is a K×N input matrix composed of all input vectors of the N DMUs. The efficiency score will satisfy $0 \leq \theta \leq 1$. If $\theta = 1$, DMU i operates on the efficiency frontier and hence is technically efficient. To control the annual environment, all of the efficiency scores and input targets for DMU i in year t can be determined by comparing them to the efficiency frontier in year t; that is, only the observations from the same year are used in the DEA model.

Target Energy Input$_{(i, j, t)}$ is defined as the following:

Actual Energy Input$_{(i, j, t)}$

- [Radial Adjustment$_{(i, j, t)}$+ Non-radial Slack Adjustment$_{(i, j, t)}$], (2)

where (i, j, t) refers to each value for the j-th industry in the i-th country in the t-th year. The radial adjustment is given by $(1-\theta)x_{(i, j, t)}$, and the non-radial slack is defined as the amount that could be reduced using the non-radial method. The total-factor energy efficiency (TFEE) index is defined as

$TFEE_{(i, j, t)}$ =Target Energy Input$_{(i, j, t)}$/Actual Energy Input$_{(i, j, t)}$. (3)

Based on the above definition, TFEE assumes a value between zero and unity. A higher TFEE implies a higher level of energy efficiency. A TFEE score of unity indicates that the industry is efficient and cannot save energy without reducing its added value. A TFEE score that is lower than unity implies that this industry is inefficient and can increase its energy-saving methods.

2.2 Data

Our energy and economic dataset contains 11 industries in 14 developed countries for the period of 1995-2005[1]. The countries include Australia, Austria, the Czech Republic, Denmark, Finland, Germany, Italy, Japan, South Korea, the Netherlands, Portugal, Sweden, the United Kingdom, and the United States. The industries include the iron and steel and non-ferrous metals industries; the chemical and petrochemical industry; the non-metallic minerals industry; the transport equipment industry; the machinery industry; the food and tobacco industry; the paper, pulp and printing industry; the wood and wood products industry; the construction industry; the textile and leather industry; and non-specified industries. Because there are no energy data for five industries[2], the total number of industries with data for each year is 149.

This model includes four inputs: labor, capital stock, intermediate inputs not including energy, and energy. Value added is the sole output. The economic data are taken from EU-KLEMS (2008). Data on purchasing power parity (PPP) is also taken from EU-KLEMS. The values for the variables are presented in 1997 Euros. The EU-KLEMS project, which is financed by the European Commission, has developed a revolutionary comprehensive database of European and other developed countries for use in analyzing economic growth and productivity. Using these data enables us to make international comparisons of industry-level efficiency.

[1] Abbreviations for countries and industries are presented in the Appendix.
[2] The following five sectors are eliminated because they lack energy consumption data: the transport equipment industry in Australia; non-specified industries in Australia; the transport equipment sector in Japan; the wood and wood products sector in Japan; and the textile and leather sector in Japan.

Table 1 Description and summary statistics of variables (1995-2005)

	Unit	Mean	Maximum	Minimum	Standard deviation
Value added	Millions of Euros 1997 price	30,610	1,371,883	235	75,968
Labor	Total hours worked by persons engaged (millions of hours)	1,062	18,764	9	2,208
Capital	Millions of Euros 1997 price	32,818	316,463	460	53,538
Intermediate inputs without energy	Millions of Euros 1997 price	49,807	794,361	545	98,949
Energy	Thousand tonnes of oil equivalent (toe)	4,214	92,500	10	9,506

Table 2 Correlation matrix for all inputs and output (1995-2005)

	Value added	Labor	Capital	Intermediate inputs without energy	Energy
Value added	1.000				
Labor	0.824	1.000			
Capital	0.776	0.742	1.000		
Intermediate inputs without energy	0.894	0.887	0.874	1.000	
Energy	0.366	0.262	0.548	0.359	1.000

Table 3 Total-factor energy efficiency by industry during 1995-2005

Industry	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
Chemical	0.854	0.846	0.808	0.830	0.818	0.814	0.798	0.710	0.531	0.470	0.381	0.715
Construction	0.887	0.862	0.886	0.883	0.902	0.868	0.863	0.848	0.807	0.657	0.594	0.823
Food	0.591	0.560	0.505	0.573	0.522	0.492	0.453	0.478	0.367	0.254	0.200	0.454
Machinery	0.692	0.677	0.736	0.769	0.766	0.764	0.730	0.702	0.619	0.470	0.467	0.672
Metal	0.510	0.469	0.454	0.451	0.400	0.451	0.434	0.331	0.305	0.368	0.298	0.406
Non-metallic	0.790	0.566	0.720	0.471	0.391	0.460	0.423	0.383	0.418	0.346	0.074	0.458
Non-specified	0.593	0.540	0.560	0.541	0.563	0.549	0.436	0.416	0.343	0.239	0.209	0.453
Paper	0.585	0.501	0.532	0.550	0.543	0.555	0.449	0.378	0.347	0.249	0.126	0.438
Textile	0.672	0.624	0.677	0.667	0.670	0.677	0.647	0.636	0.579	0.498	0.437	0.617
Transport	0.791	0.776	0.789	0.772	0.781	0.722	0.729	0.676	0.606	0.496	0.458	0.690
Wood	0.674	0.674	0.627	0.631	0.606	0.664	0.643	0.598	0.553	0.517	0.418	0.600

Data regarding energy consumption are taken from the Energy Balances of OECD Countries (International Energy Agency). Economic and energy-related data for various industries are then matched using the above data sources.

Table 1 summarizes the statistics for these inputs and the output. Table 2 presents a correlation matrix.

3. Empirical Results

3.1 TFEE by industry

Table 3 shows the average TFEE for each industry. On average, during the total period, the least efficient industry is the metal industry, and the second-least efficient is the paper industry; the data indicating the

Table 4 The number of efficient industries

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Number of efficient industries	26	28	31	31	31	29	25	20	19	15	11

third-worst level of efficiency correspond to the non-specified industries. Among the energy-intensive industries (e.g., chemical, metal, non-metallic, and paper), the chemical industry has a relatively higher average TFEE score of 0.715, whereas the average TFEE scores from the other three are lower than 0.5. Although the food industry is not energy-intensive, its TFEE scores are low, with an average score of 0.454.

Next, we compare the TFEE figures with the traditional energy efficiency index, i.e., energy intensity as a direct ratio of energy input to GDP. nergy intensity only takes energy into account as an input and neglects other inputs such as labor and capital. In contrast, the TFEE index includes both energy and non-energy inputs. The correlation between TFEE and energy intensity in our sample is -0.455. TFEE scores provide a partially (but not entirely) different measurement of energy efficiency.

The TFEEs of all industries decline during the sample period because DEA measures the relative efficiency of DMUs in each year. If a few industries substantially improve their energy efficiency in t+1 year, the remaining industries may be deemed inefficient in that year if their inputs and output are the same as they were in *t* year. As Table 4 shows, the number of efficient industries tends to decrease during the sample period. The results do not indicate that worldwide energy efficiency worsened from 1995 to 2005. Rather, the energy efficiency of the countries that were studied is divergent rather than convergent. The number of efficient industries with a unity TFEE score declines during the sample period, with 26 industries in 1995 and 31 during the period of 1997-1999; however, the number decreases to 11 in 2005.

This research focuses on the TFEE scores of four major industries: the chemical, machinery, metal, and non-metallic industries, as presented in Tables 5 through 8, respectively. For the chemical industry, only the Netherlands achieves a unity TFEE score throughout the sample period (Table 5). Except in 2005, Sweden obtains a unity TFEE score. Other countries that obtain higher TFEE scores before 2002 obtain lower scores from 2002 to 2003. In the machinery industry, Finland, Sweden, and the United States achieve relatively higher TFEEs (Table 6). Only South Korea, Sweden, and the United States improve their TFEEs from 1995 to 2005. In the metal industry, only Denmark achieves a unity TFEE score during the sample period (Table 7). Finland, the Netherlands, and Sweden improve their TFEE scores from 1995 to 2005. Australia and the United Kingdom have very low TFEE scores of less than 0.2 throughout the sample period. In the non-metallic industry, no country has consistent unity TFEE

Table 5 Total-factor energy efficiency for the chemical industry

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
AUS	0.311	0.264	0.225	0.359	0.319	0.242	0.175	0.351	0.218	0.121	0.110
AUT	0.806	0.832	0.706	0.684	0.760	0.784	0.718	0.740	0.602	0.519	0.287
CZE	0.682	0.716	0.511	0.483	0.470	0.445	0.464	0.486	0.374	0.137	0.051
DNK	1.000	0.973	0.932	1.000	1.000	1.000	1.000	0.943	0.803	0.664	0.553
FIN	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.978	0.855	0.831	0.731
GER	0.981	0.969	0.973	0.966	0.879	0.925	0.938	0.512	0.478	0.470	0.371
ITA	0.843	0.823	0.823	0.819	0.823	0.818	0.754	0.670	0.584	0.496	0.403
JPN	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.900	0.290	0.283	0.278
KOR	0.762	0.747	0.852	0.900	0.852	0.901	0.932	0.637	0.582	0.420	0.402
NLD	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
PRT	0.592	0.619	0.435	0.585	0.576	0.504	0.395	0.386	0.259	0.221	0.160
SWE	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.718
UK	0.980	0.901	0.851	0.828	0.776	0.777	0.790	0.341	0.284	0.309	0.180
USA	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.107	0.102	0.090

Table 6 Total-factor energy efficiency for the machinery industry

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
AUS	0.311	0.264	0.225	0.359	0.319	0.242	0.175	0.351	0.218	0.121	0.110
AUT	0.806	0.832	0.706	0.684	0.760	0.784	0.718	0.740	0.602	0.519	0.287
CZE	0.682	0.716	0.511	0.483	0.470	0.445	0.464	0.486	0.374	0.137	0.051
DNK	1.000	0.973	0.932	1.000	1.000	1.000	1.000	0.943	0.803	0.664	0.553
FIN	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.978	0.855	0.831	0.731
GER	0.981	0.969	0.973	0.966	0.879	0.925	0.938	0.512	0.478	0.470	0.371
ITA	0.843	0.823	0.823	0.819	0.823	0.818	0.754	0.670	0.584	0.496	0.403
JPN	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.900	0.290	0.283	0.278
KOR	0.762	0.747	0.852	0.900	0.852	0.901	0.932	0.637	0.582	0.420	0.402
NLD	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
PRT	0.592	0.619	0.435	0.585	0.576	0.504	0.395	0.386	0.259	0.221	0.160
SWE	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.718
UK	0.980	0.901	0.851	0.828	0.776	0.777	0.790	0.341	0.284	0.309	0.180
USA	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.107	0.102	0.090

Table 7 Total-factor energy efficiency for the metal industry

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
AUS	0.195	0.180	0.140	0.170	0.079	0.072	0.071	0.071	0.069	0.035	0.017
AUT	0.192	0.449	0.334	0.338	0.243	0.232	0.167	0.182	0.287	0.124	0.154
CZE	0.473	0.194	0.404	0.128	0.178	0.228	0.079	0.106	0.315	0.175	0.043
DNK	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
FIN	0.304	0.401	0.416	0.412	0.376	0.327	0.310	0.383	0.342	1.000	0.551
GER	0.471	0.647	0.494	0.473	0.325	0.331	0.342	0.136	0.120	0.173	0.154
ITA	0.878	0.836	0.856	0.893	0.751	0.814	0.742	0.315	0.306	0.282	0.298
JPN	1.000	0.324	0.333	0.315	0.318	1.000	0.990	0.698	0.263	0.261	0.257
KOR	0.407	0.426	0.350	0.469	0.408	0.442	0.466	0.188	0.195	0.258	0.286
NLD	0.142	0.161	0.120	0.188	0.149	0.163	0.232	0.217	0.209	0.378	0.372
PRT	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.918	0.762	0.694	0.379
SWE	0.237	0.257	0.235	0.326	0.290	0.281	0.282	0.236	0.248	0.423	0.324
UK	0.187	0.102	0.120	0.158	0.125	0.110	0.096	0.085	0.069	0.159	0.148
USA	0.649	0.597	0.555	0.443	0.352	0.319	0.304	0.105	0.082	0.186	0.184

Table 8 Total-factor energy efficiency for the non-metallic industry

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
AUS	0.570	0.257	0.251	0.225	0.173	0.251	0.108	0.192	0.329	0.164	0.042
AUT	0.909	0.723	0.692	0.761	0.817	0.849	0.911	0.818	0.748	0.623	0.092
CZE	0.762	0.392	0.709	0.425	0.386	0.518	0.539	0.487	0.455	0.403	0.082
DNK	0.744	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.104
FIN	1.000	1.000	0.628	0.648	0.587	0.931	0.576	0.579	0.772	0.624	0.204
GER	0.454	0.459	0.858	0.360	0.427	0.376	0.401	0.145	0.142	0.079	0.044
ITA	0.787	0.784	0.762	0.690	0.669	0.638	0.666	0.160	0.092	0.029	0.034
JPN	0.802	0.537	0.810	0.093	0.015	0.021	0.044	0.099	0.126	0.073	0.032
KOR	0.606	0.056	0.593	0.081	0.076	0.091	0.106	0.161	0.126	0.104	0.030
NLD	0.754	0.631	0.501	0.465	0.351	0.423	0.248	0.426	0.534	0.491	0.106
PRT	0.797	0.320	0.779	0.277	0.223	0.287	0.298	0.304	0.363	0.358	0.046
SWE	0.934	0.679	0.565	0.497	0.480	0.663	0.761	0.599	0.754	0.580	0.146
UK	0.941	0.092	0.925	0.064	0.088	0.263	0.129	0.333	0.349	0.294	0.057
USA	1.000	1.000	1.000	1.000	0.183	0.133	0.131	0.058	0.060	0.016	0.020

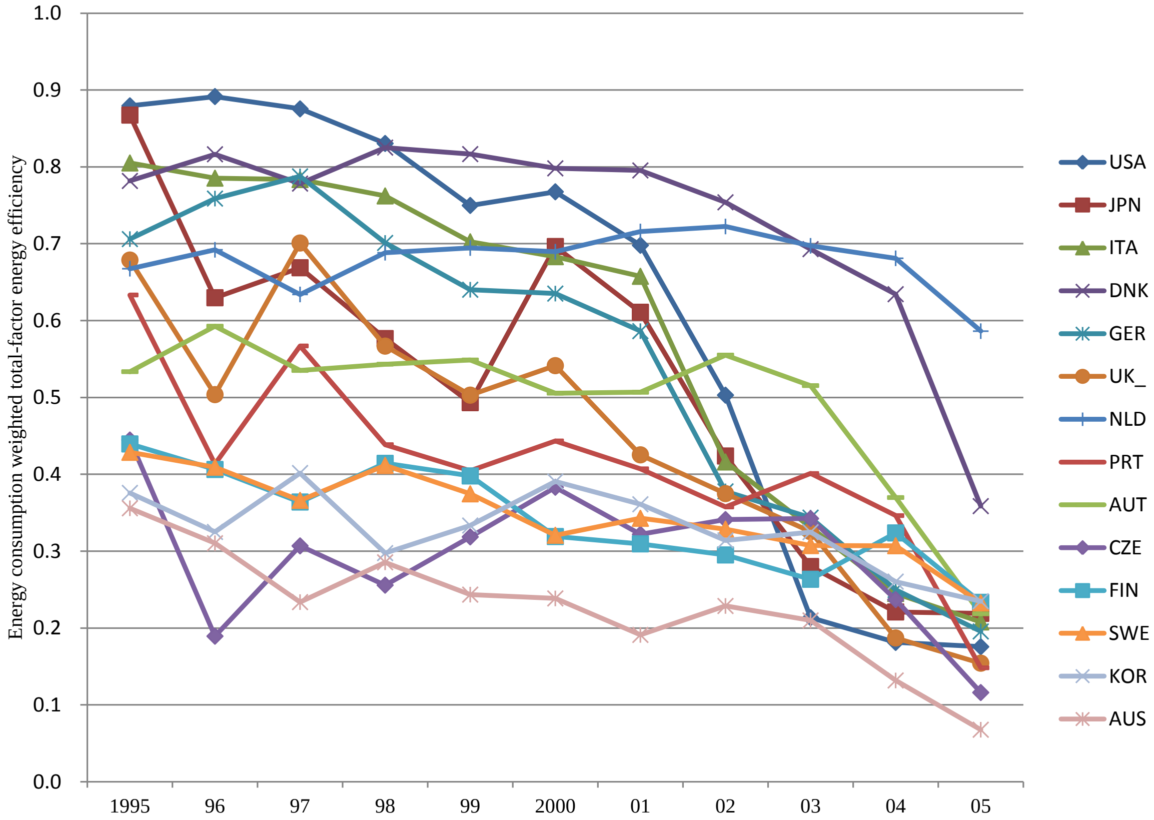

Figure 1 Energy consumption weighted total-factor energy efficiency by country

scores (Table 8)[3]. Denmark achieves unity TFEE scores from 1996 to 2004.

3.2 TFEE by country

Next, we compare energy efficiency levels by country. The figures for each industry vary considerably from one country to the next. Here, we

[3] From 2004 to 2005, all of the countries except Germany, Italy, and the United States decrease their TFEE scores by more than 50%. These drastic changes may be attributed to the fact that our DEA methodology is based on linear programming.

compare weighted average TFEE figures: Each country's weighted average TFEE is the sum of each industry's TFEE multiplied by the share of its industry in that country. As Figure 1 shows, Australia is the most inefficient country except in the years 1996 and 1998. The most efficient countries are the United States from 1995 to 1998, Denmark from 1999 to 2002, and the Netherlands from 2003 to 2005.

As Figure 1 shows, the average TFEE for each country decreases during the sample period. The United States TFEE drops from 0.879 in 1995 to 0.176 in 2005, the TFEE for Japan drops from 0.867 to 0.219, and the TFEE for Italy drops from 0.805 to 0.208. In contrast, the countries whose TFEEs exhibit less change are the Netherlands, South Korea, and Sweden. The Netherlands falls from 0.667 in 1995 to 0.586 in 2005, South Korea falls from 0.376 to 0.235, and Sweden falls from 0.429 to 0.233.

3.3 Potential energy saving

We can use the difference between actual energy input and target energy input to determine potential energy savings. Figure 2 shows the potential energy savings for the sample countries in 1995-2005. The total potential energy savings more than triples from 146.9 million tonnes of oil equivalent (toe) in 1995 to 504.4 million toe in 2005. These findings are consistent with the aforementioned downward trend in TFEE. The United States has the greatest energy saving potential throughout the research period, except in 1996. Japan has the second-greatest degree of potential after 1997. The United States, Japan, Germany, and South Korea also show a high

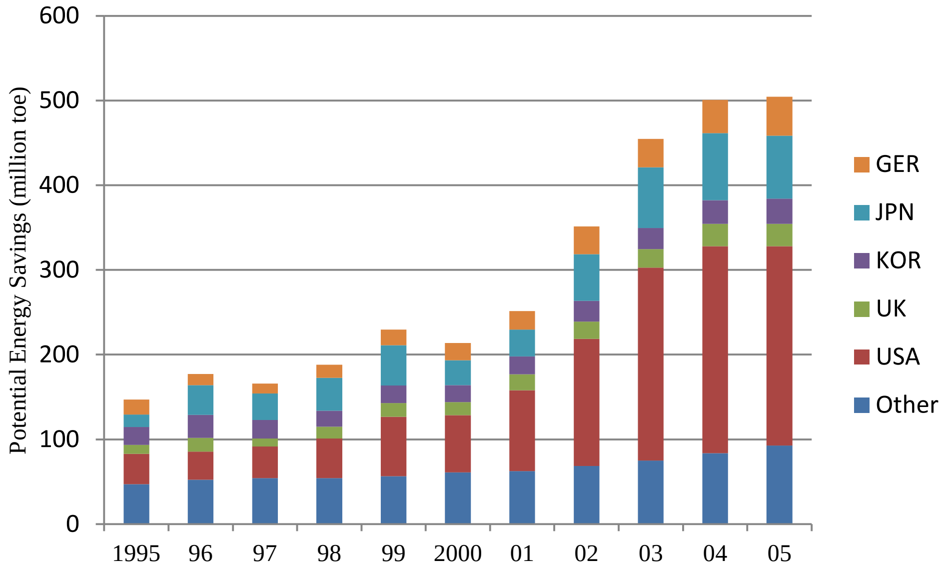

Figure 2 Potential energy savings for the sample countries, 1995-2005

degree of potential. This outcome is not surprising, as energy consumption itself is substantial in these countries.

As shown in Table 9, the metal industry exhibits the greatest share of potential energy savings from 1995 to 2002, making up more than one-third of the total in 1995-1999. After 1997, however, this industry's share gradually declines, and the chemical industry has the greatest share in the remainder of the sample period. During the sample period (except for the non-specified industries[4]), the metal (share of total potential energy saving during the sample period is 24.9%, hereinafter the same), paper (14.5%), non-metallic (13.9%), and chemical (12.0%) industries were the ones with the most potential for additional energy consumption.

[4] Because this category contains the rest of the manufacturing sector and is composed of various industries, analytical results for these industries require more detailed categorized data.

Table 9 Share of total potential energy saving by industry each year

Industry	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Share
Chemical	3.1%	3.7%	3.2%	2.7%	2.9%	3.2%	2.8%	5.0%	23.0%	21.5%	21.9%	12.0%
Construction	0.5%	0.5%	0.4%	0.5%	0.2%	0.4%	0.3%	0.2%	0.3%	0.5%	0.7%	0.4%
Food	7.8%	8.1%	10.3%	8.6%	8.9%	11.3%	10.6%	9.3%	8.7%	9.3%	9.5%	9.3%
Machinery	5.7%	3.4%	3.2%	2.3%	2.3%	2.4%	2.6%	1.8%	2.4%	2.9%	3.4%	2.8%
Metal	36.7%	37.0%	41.4%	37.2%	33.5%	29.0%	24.6%	23.1%	18.7%	16.8%	16.6%	24.9%
Non-Metallic	8.5%	13.3%	6.5%	15.4%	19.8%	22.6%	19.3%	14.8%	11.6%	11.6%	12.4%	13.9%
Non-specified	13.6%	12.9%	12.3%	10.7%	11.9%	12.7%	17.3%	16.6%	12.6%	13.4%	10.6%	13.1%
Paper	13.7%	10.6%	9.8%	9.2%	7.9%	9.7%	12.2%	21.3%	16.3%	16.9%	17.3%	14.5%
Textile	4.5%	4.0%	3.5%	3.7%	3.5%	3.6%	3.6%	3.0%	2.4%	2.5%	2.5%	3.1%
Transport	1.0%	0.9%	0.8%	0.9%	0.9%	1.7%	1.3%	1.2%	1.6%	1.9%	2.2%	1.5%
Wood	4.9%	5.6%	8.6%	8.8%	8.2%	3.4%	5.3%	3.6%	2.5%	2.6%	2.7%	4.3%

Note: Share means that of total potential energy saving during the sample period.

Lastly, we consider the relationship between per capita potential energy savings (PPES) in each industry and per capita GDP. PPES is calculated as the potential energy savings divided by the population.

In previous studies (Hu and Wang, 2006; Hu and Kao, 2007; Honma and Hu, 2008), a relationship between per capita GDP and aggregate energy efficiency or potential energy savings is considered. However, disaggregate energy efficiency and potential energy savings vary across industries within a given country. Therefore, when considering the relationship between energy efficiency and income, one must examine both national energy efficiency and industry energy efficiency levels.

We employ a Tobit regression model to investigate the relationship

Table 10 Tobit regression of per capita energy savings for 11 industries

Variable	*Constant*	*Year*	*lnGDPpc*	$(lnGDPpc)^2$	Log likelihood
Chemical	13.882***	0.010***	-2.790***	0.140***	137.100
	(3.209)	(6.773)	(3.156)	(3.095)	
Construction	1.427	0.002***	-0.278	0.013	162.188
	(0.806)	(4.377)	(0.767)	(0.721)	
Food	7.205***	0.002***	-1.489***	0.077***	343.949
	(3.237)	(2.594)	(3.276)	(3.325)	
Machinery	0.695	0.003***	-0.101	0.003	332.083
	(0.482)	(5.964)	(0.344)	(0.208)	
Metal	1.844	-0.001	-0.390	0.022	64.365
	(0.169)	(0.147)	(0.175)	(0.191)	
Non-Metallic	3.412	0.007***	-0.619	0.028	252.576
	(1.111)	(6.95)	(0.987)	(0.868)	
Non-specified	-1.213	0.000	0.195	-0.007	139.612
	(0.106)	(0.118)	(0.083)	(0.054)	
Paper	-46.719**	0.010	9.464**	-0.478**	-13.714
	(2.059)	(1.384)	(2.042)	(2.021)	
Textile	-4.273	0.000	0.874	-0.045	258.670
	(1.61)	(0.73)	(1.6)	(1.587)	
Transport	-3.816***	0.001***	0.774***	-0.039***	333.176
	(2.834)	(4.231)	(2.8)	(2.766)	
Wood	-10.899***	0.001	2.260***	-0.117***	275.303
	(3.239)	(1.621)	(3.267)	(3.291)	

Note: Numbers in parentheses are z-values. *** and ** denote significance at the 1% and 5% level, respectively.

between the PPES of each industry and income because the PPES is left-censored at zero. Note that the PPES equals zero when the industry has a unity TFEE score. We used the following equation for specific industries:

$$PPES_{ijt} = \beta_0 + \beta_1 \, lnGDPpc_{it} + \beta_2 \, (lnGDPpc_{it})^2 + t + u_{it}, \qquad (3)$$

where $PPES_{ijt}$ and $lnGDPpc_{it}$ are PPES and the natural log of the per capita GDP of the i-th country in year t, respectively, and u_{it} is an error term that follows a normal distribution. Table 10 shows the results of the Tobit regression. The positive sign for GDP per capita and the negative sign of the quadratic term for GDP per capita confirm the inverse U-shaped relationship between PPES and income. This relationship is similar to the environmental Kuznets curve (EKC) hypothesis in which pollution levels increase as per capita income increases but then begin to decease beyond a certain point; environmental load decreases as income rises but then begins to increase. There is a significant U-shaped relationship between PPES and per capita GDP for the paper, transport, and wood industries. In contrast, there is a significant inverse U-shaped relationship between PPES and per capita GDP for the chemical and food industries. The remaining industries show insignificant coefficients for the quadratic term. We conclude that whether potential energy saving increases or decreases when income increases varies across industries. Except in the metal industry, the time trend parameter is positive, showing an increase in potential energy savings per capita over time.

4. Concluding Remarks

This paper computes and analyzes the energy efficiency of 11 industries in 14 developed countries using a total-factor framework. The TFEE can be obtained by comparing the target energy inputs obtained via DEA to the actual energy input. Production technology varies from industry to industry. However, if the goal is to decrease energy consumption without lowering economic value, we should consider not only improving energy efficiency of inefficient countries within particular industries but also changing the relevant industrial structures to convert industries from energy consuming to energy efficient.

The most inefficient industry is the metal industry, with an average TFEE of 0.406. Based on the average TFEE figures (which reflect the energy consumption of each industry), Australia is the most inefficient country, except in the years 1996 and 1998. The most efficient countries are the United States from 1995 through 1998, Denmark from 1999 through 2002, and the Netherlands from 2003 through 2005.

The number of efficient industries with unity TFEE scores decreases during the sample period. Contrary to the belief that country-level energy efficiency differences decrease over time, this study does not find that TFEE scores converge at the individual industry level. It would appear that, as the global total-factor efficiency (technology) frontier shifts up, the opportunities for most countries to improve their energy efficiency become increasingly greater. In addition, upon comparing PPES and TFEE scores, we find that the relationship between the two scores varies across industries. Using Tobit regression, we find that the paper, transport, and wood industries exhibit a significant inverse U-shaped relationship between PPES and per capita GDP, whereas the chemical and food industries exhibit significant U-shaped relationships. It may be interesting to explore these relationships further in future research.

At the same time, industries in less-efficient countries still survive by inefficiently using various inputs and government subsidies and neglecting environmental costs. It remains unclear what factors affect industry-level energy efficiency and what factors prevent the convergence of energy efficiency indices. For these purposes, additional data on energy policy and prices in particular countries will be required.

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Appendix: Abbreviations of the countries and industries in this study

No.	Country	Abbreviation	No.	Industry	Abbreviation
1	Australia	AUS	1	Chemical and Petrochem.	Chemical
2	Austria	AUT	2	Construction	Construction
3	Czech Republic	CZE	3	Food and Tobacco	Food
4	Denmark	DNK	4	Machinery	Machinery
5	Finland	FIN	5	lron and Steel, and Non-Ferrous Metals	Metal
6	Germany	GER	6	Non-Metallic Minerals	Non-Metallic
7	Italy	ITA	7	Non-specified	Non-specified
8	Japan	JPN	8	Paper, PuIp and Printing	Paper
9	South Korea	KOR	9	Textile and Leather	Textile
10	Netherlands	NLD	10	Transport Equipment	Transport
11	Portugal	PRT	11	Wood and Wood Products	Wood
12	Sweden	SWE			
13	United Kingdom	UK			
14	United States	USA			