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Industry-level total-factor energy efficiency in developed countries: A Japan-centered analysis

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HIGHLIGHTS

- This study compares Japan with other developed countries for energy efficiency at the industry level.
- We compute the total-factor energy efficiency (TFEE) for industries in 14 developed countries in 1995–2005.
- Energy conservation can be further optimized in Japan's industry sector.
- Japan experienced a slight decrease in the weighted TFEE from 0.986 in 1995 to 0.927 in 2005.
- Japan should adapt energy conservation technologies from the primary benchmark countries: Germany, UK, and USA.

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ABSTRACT

Japan's energy security is more vulnerable today than it was before the Fukushima Daiichi nuclear power plant accident in March 2011. To alleviate its energy vulnerability, Japan has no choice but to improve energy efficiency. To aid in this improvement, this study compares Japan's energy efficiency at the industry level with that of other developed countries. We compute the total-factor energy efficiency (TFEE) of industries in 14 developed countries for 1995–2005 using data envelopment analysis. We use four inputs: labor, capital stock, energy, and non-energy intermediate inputs. Value added is the only relevant output. Results indicate that Japan can further optimize energy conservation because it experienced only a marginal decrease in the weighted TFEE, from 0.986 in 1995 to 0.927 in 2005. To improve inefficient industries, Japan should adapt energy conservation technologies from benchmark countries such as Germany, the United Kingdom, and the United States.

1. Introduction

Efficient energy consumption is a top priority in the environmental field in terms of both resource conservation and combating climate change. In general, accepting declining economic growth as a consequence of decreased energy consumption is not acceptable. Therefore, improving energy efficiency without impairing economic performance is important for every economy.

The Fukushima Daiichi nuclear power plant accident following the Tohoku earthquake and tsunami in March 2011 prompted a reformation in Japan's energy policy. Before the Fukushima incident, nuclear energy produced approximately 30% of Japan's electricity; however, the enormous radioactive release and ensuing evacuation spurred an anti-nuclear energy movement in Japan. Even with periodically regulated monitoring after the earthquake, no Japanese nuclear power plant was allowed to resume operations. This was because the national government was unable to promptly revise its nuclear power plant safety standards and both mayors and citizens residing near nuclear power plants opposed resuming operations. All of Japan's 54 nuclear power plants ceased operations on May 5th, 2012. Only the Ohi nuclear power plant restarted in July 2012, because of severe electricity shortages in the Kansai region, but it ceased again for periodic inspection in September 2013.

The Japanese government has promoted nuclear energy for two reasons. First, to improve Japan's energy security. In 2010, Japan imported 96% of its primary energy supply and relied on imported oil for 99.6% of domestic demand. Moreover, 86.6% of Japan's imported crude oil comes from the politically unstable Middle East. Second, Japan targeted nuclear power as a primary means to reduce carbon dioxide emissions. In fact, prior to the Fukushima incident, the Japanese government planned to build 14 more reactors and increase the share of nuclear power in the nation's electricity supply to 50% by 2030.

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The Fukushima incident and ensuing public opposition prompted drastic changes in Japan's energy policies. Japan no longer depends on nuclear energy for electricity generation [1]. The Japanese government is currently promoting renewable energy to compensate for the loss of nuclear power and has implemented a feed-in tariff scheme for it. However, even high-level penetration of renewable energy cannot fully replace nuclear power [2].

Japan's energy security is more vulnerable today than it was before the accident. Japan has no choice but to improve its energy efficiency to alleviate its energy vulnerability. The nation responded to the two oil crises in the 1970s by enhancing energy-saving technology; however, little progress was made during the 1980s and 1990s. Japan still has potential to improve energy savings [3]. To assist policymakers in this regard, this study compares Japan's energy efficiency at the industry level with that of other developed countries.

Since the first oil crisis in 1973, many major developed countries have implemented measures to improve energy efficiency [4]. Recently, the European Council advocated ambitious targets, known as the 20/20/20 goals [5]:

- Reduce greenhouse gas (GHG) emissions 20% from 1990 levels by 2020.
- Increase energy efficiency to reduce EU energy consumption 20% by 2020.
- Ensure that 20% of all EU energy consumption comprises renewable energy by 2020.

Energy efficiency appears to be the only item among these goals that will reduce GHG emissions, improve energy stability, cut energy costs, and enhance economic competitiveness [6]. Therefore, energy efficiency can be portrayed as Europe's biggest energy source [7]. It is important to note that improving energy efficiency can aid in the reduction of GHGs and boost the share of renewable energy without new investment [8]. One driver of improved energy efficiency in the industrial sector is technological change, which is critically affected by the political framework and stringent standards of carbon dioxide reduction [9]. Thus, the importance of energy efficiency targets in policymaking cannot be overemphasized.

Unfortunately, the EU's current 20/20/20 policy may be naïve and suboptimal. Uniform application of goals for all EU members is neither fair nor equitable because energy efficiency among countries varies [10]. The simulation by Capros et al. [11] shows that the EU energy policy is likely to cause an undesirable distributional impact; therefore, targets should be set with consideration for fairness. A country's energy consumption savings should be differentiated on the basis of each country's current efficiency.

Disaggregated information about energy efficiency is essential in establishing well-designed energy efficiency targets. Because not all energy sources are perfectly substitutable in every region, the quality of energy problem [12,13] should be considered. Although substitutability and price differences among sources must be examined in terms of energy aggregation, the traditional energy intensity (EI) indicator—energy consumption per unit of GDP—is used in formal statistics [6]. Most EI studies show that levels tend to converge [14–19]; however, certain studies indicate that a convergence of EI appears only in some regions [20,21]. Mendiluce et al. [22] claim that while EI in Spain increases owing to growth in transportation, it decreases in other EU countries.

Government programs and academic research use energy productivity (EP), defined as output per unit of energy consumption, alongside EI. However, EI or EP frameworks are not included, wherein other inputs such as labor and capital can be substituted with energy [23]. As Patterson [24] notes, the EP ratio can be reduced simply by substituting labor with energy. Therefore, energy efficiency should be evaluated using a multiple input–output model. The data envelopment analysis (DEA) approach, a non-parametric method of linear programming, suits this purpose.

Table 1
Industry list.

Industry classification	Description
Chemical	Chemical and petrochemical
Construction	Construction
Food	Food and tobacco
Machinery	Machinery
Metal	Iron and steel, non-ferrous metals
Non-metallic minerals	Non-metallic minerals
Paper	Paper, pulp, and printing
Textile	Textile and leather
Transport	Transport equipment
Wood	Wood and wood products

The purpose of this study evaluates industry-level total-factor energy efficiency of 14 developed countries and compares Japan's energy efficiency with that of other countries. Using the DEA approach, we calculate the total-factor energy efficiency (TFEE) index proposed in Hu and Wang [25]. We regard DEA as the best tool for this purpose, as it explicitly indicates the potential saving of inputs through efficiency calculation.

Few studies of industry-level energy efficiency exist because, even for developed countries, no industry-level, internationally compatible, credible data are derived using a uniform method regarding capital stock. However, the EU KLEMS [26] project, financed by the European Commission, has developed a comprehensive database for developed countries, allowing researchers to internationally compare industry-level efficiency.

This study is organized as follows: Section 2 reviews relevant literature. Section 3 presents our methodology and data. Section 4 compares energy efficiency between Japan and other developed countries, provides sensitivity analyses, and compares the results with traditional EP. Section 5 concludes this paper.

2. Literature review[1]

When modeling industrial energy efficiency evaluation, researchers must conciliate data availability, the level of disaggregation, and modeling efforts for adequate sectoral representation [27]. Numerous studies address improvements in industrial energy efficiency, commonly through case studies that explore energy efficiency improvements in selected industries. Jochem and Gruber [28] analyze the effect of local leaning networks on energy efficiency in Germany, identifying preconditions and factors of successful networks. Klugman et al. [29] investigate a Scandinavian chemical wood-pulp mill using an energy audit and identify energy-saving points. Usón et al. [30] analyze energy efficiency assessment and improvement in a coal-fired plant by using a thermo-economic diagnosis system, demonstrating its commendable accuracy for sources of inefficiency.

Ammar et al. [31] examine low-grade heat recovery in process industries, identifying low-grade heat sources and their potential markets in the United Kingdom. Investigating the paper industry in the Netherlands, Poland, and Sweden, Laurijssen et al. [32] find that the natural gas combined cycle prevalent in the Netherlands uses the least energy. Cagno and Trianni [33] investigate 71 small- and medium-sized Italian manufacturing enterprises in multiple case studies, finding that the crucial motivators to adopting energy-efficient technologies are allowances or public financing, external pressures, and long-term benefits. Analyzing 65 foundries in seven European countries, Thollander et al. [34] find that

[1] We thank one of the referees for indicating relevant literature.

Table 2
Summary of statistics.

Variable	Value added	Labor	Capital stock	Non-energy intermediate inputs	Energy
Unit	1995 price (million euros)	Total hours worked by persons engaged (million hours)	1995 price (million euros)	1995 price (million euros)	Oil equivalent (million tons)
Average	30676.71698	1048.164969	33095.77965	50413.529	4102.372995
Standard deviation	78165.90432	2254.52346	54868.84606	101978.8203	9635.986212
Min	235.2913217	8.871592431	459.6726533	544.922273	10
Max	1371882.94	18764.47287	316462.8206	794361.2266	92500
Observation	1496	1496	1496	1496	1496

Table 3
TFEEs for the chemical industry.

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Australia	0.368	0.335	0.315	0.455	0.240	0.205	0.304	0.627	0.390	0.496	0.530
Austria	0.570	0.605	0.560	0.571	0.673	0.652	0.803	0.645	0.596	0.499	1.000
Czech Republic	0.438	0.529	0.633	0.404	0.274	0.257	0.397	0.575	0.310	0.237	0.346
Denmark	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Finland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000	0.987	1.000	1.000	1.000	1.000	1.000
Italy	0.843	0.823	0.823	0.819	0.823	0.818	0.754	0.796	0.777	0.759	0.730
Japan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.956	0.934
South Korea	0.921	0.863	0.992	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Netherlands	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Portugal	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Sweden	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United Kingdom	1.000	1.000	0.962	0.897	0.878	0.825	0.827	0.742	0.769	0.775	0.855
United States	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

financial and organizational issues are perceived as the most relevant forces for driving improved energy efficiency. Seck et al. [27] develop a bottom-up energy model for non-energy-intensive industries in France and document the impact of heat recovery with heat pumps in the food and drink industry.

On the other hand, industry-specific models quantitatively present potential for conserving energy and reducing carbon dioxide emissions. Using physical production data, Farla et al. [35] apply an index composition approach to the pulp and paper industry in eight countries from the Organisation for Economic Co-operation and Development (OECD). They show that growth of primary energy consumption in this industry was limited to 16% between 1973 and 1991 because of energy efficiency improvements, whereas production increased by 42% in the sampled countries. Siitonen et al. [36] shed light on differences in process heat conservation from the mill site and national levels in Finland's pulp and paper industry.

Although studies of industry-specific improvements in energy efficiency involve case studies and industry-specific models, scholars usually employ a unified framework when investigating energy efficiency at national, regional, and industrial levels. DEA is among the most suitable methods for measuring energy efficiency.[2]

Numerous studies evaluate economy-wide aggregate energy efficiency using the DEA approach.[3] Hu and Kao [41] measure energy efficiency of 17 Asia–Pacific Economic Cooperation (APEC) economies, and Zhou and Ang [42] do so for 21 OECD countries. Moreover, Sözen and Alp [43] use the DEA method to evaluate energy consumption, GHG emissions, and local pollutants in Turkey and 28 EU countries including Switzerland. Lozano and Gutiérrez [44] propose three models for evaluating efficiency using population, GDP, energy consumption, and GHG emissions and employed them to study 28 Annex B countries from the Kyoto Protocol. Wang et al. [45] apply multidirectional efficiency analysis to Chinese regional energy and emission efficiency.

The above-mentioned papers analyze national energy efficiency; other studies apply DEA to specific industries. Oggioni et al. [46] provide different eco-efficiency measurements of the cement industry in 21 countries, taking carbon dioxide emissions as inputs or undesirable outputs. Wang et al. [47] use a Malmquist–Luenberger index to measure cost efficiency of China's thermal power industry.

Although information regarding aggregate energy efficiency is useful, it provides only an approximate estimation of nationwide energy consumption. Countries generally have efficient and inefficient industries, and aggregate efficiency scores cannot determine which of these need improvement. Furthermore, more in-depth analysis requires disaggregated data for energy efficiency across countries.

Hinchy et al. [48] employ DEA to measure energy efficiency of 37 industries in 30 countries using 1992 data. They compute potential energy savings and reductions in carbon dioxide emissions on the basis of efficient targets; however, they use data from the Global Trade Analysis Project (GTAP) database.[4] Because GTAP operates economic simulation models using data from comparative studies , it is not recommended and indeed problematic, such as [48]. Mukherjee [49] uses four DEA models to measure energy efficiency of the six US sectors with the highest energy consumption, finding that the paper and allied products sector used energy more efficiently than manufacturing overall. Honma and Hu [50] measure the TFEE of 17 Japanese industries, demonstrating that Japan's energy-inefficient sectors include

[2] DEA is also widely used in resource and environmental economics [37–39].

[3] Stochastic frontier analysis is an alternative to the DEA approach, but its recent applications in energy efficiency studies are few, according to Zhou et al. [40].

[4] GTAP is a multiregion, multisector, computable general equilibrium model that computes the impact of a change in trade policy.

Table 4
TFEEs for the construction industry.

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Australia	0.209	0.141	0.156	0.117	1.000	0.293	1.000	1.000	1.000	1.000	1.000
Austria	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Czech Republic	0.454	0.503	0.399	0.276	0.569	0.568	0.519	0.511	0.563	0.560	0.578
Denmark	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Finland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Italy	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Japan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
South Korea	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.969	1.000	1.000	1.000
Netherlands	0.738	0.558	0.585	0.434	0.837	0.940	0.949	0.937	0.788	0.815	0.952
Portugal	0.323	0.370	0.361	0.302	0.670	0.632	0.609	0.626	0.675	0.638	0.674
Sweden	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United Kingdom	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United States	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 5
TFEEs for the food industry.

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Australia	0.590	0.555	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.493	0.474
Austria	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Czech Republic	0.973	0.824	0.733	0.769	0.738	0.630	0.534	0.531	0.432	0.459	0.440
Denmark	0.910	0.832	1.000	0.775	0.887	0.905	0.844	0.619	0.612	0.678	0.579
Finland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.982	1.000	1.000	1.000
Italy	1.000	1.000	0.991	0.946	0.870	0.883	0.885	0.837	0.823	0.735	0.736
Japan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
South Korea	0.493	0.535	0.461	0.624	0.638	0.640	0.717	0.668	0.652	0.683	0.618
Netherlands	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Portugal	1.000	0.868	0.806	0.823	0.866	0.588	0.490	0.404	0.472	0.510	0.490
Sweden	1.000	1.000	1.000	1.000	1.000	1.000	0.935	0.883	0.887	0.834	0.847
United Kingdom	0.979	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United States	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 6
TFEEs for the machinery industry.

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Australia	0.664	0.885	0.885	0.894	0.941	0.914	0.714	0.889	0.864	0.797	0.782
Austria	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.936	0.782	0.772	0.528
Czech Republic	0.294	0.601	0.573	0.581	0.604	0.492	0.352	0.241	0.267	0.304	0.248
Denmark	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Finland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.768	0.559
Italy	1.000	1.000	1.000	0.939	0.827	0.758	0.724	0.606	0.455	0.292	0.246
Japan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.846	0.708	0.516
South Korea	0.889	0.849	0.803	0.785	0.742	1.000	1.000	1.000	0.587	0.365	0.363
Netherlands	0.517	0.432	0.538	0.484	0.455	0.479	0.412	0.335	0.381	0.399	0.246
Portugal	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Sweden	0.852	0.752	0.636	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United Kingdom	1.000	1.000	0.973	0.967	0.890	0.786	0.734	0.644	0.404	0.156	0.350
United States	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

energy-intensive industries as well as agriculture, forestry and fishery, transportation, and communication industries.

Researchers have used the TFEE index proposed in [25] to investigate China's regional and national economies [51,52], China's industrial sector [53], APEC economies [41], Japan [54,55], and Taiwan [56]. Furthermore, researchers have adopted the same input slack-based approach to compute regional water efficiency in China [37].

Apart from the DEA approach, Miketa and Mulder [57] examine EPs of 10 manufacturing sectors in 56 developed and developing countries. They conclude that cross-country differences in EP tend to decline but that the convergence of EI is locally limited. Mulder and de Groot [58] investigate EPs of 14 sectors in 14 OECD countries along with labor productivity and conclude that convergence of EI depends on unspecified country-specific characteristics.

Previous country-comparative studies measure energy efficiency by country for nationwide energy use [40–44], by country for a particular industry's energy use [46,47], by region within a country [45,51–56], and by industry within a country [49,50]. Relatively fewer studies, such as [48], reveal industry-level energy efficiency and potential energy savings across countries. This study employs the TFEE concept advocated by Hu and Wang [25], defined as the ratio of the target energy input, as suggested by the DEA, to actual energy input. Furthermore, this study is the first to apply the TFEE score to measure industry-level energy efficiency across countries.

Table 7
TFEEs for the metal industry.

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Australia	1.000	0.435	0.417	0.401	0.295	0.346	0.385	0.406	0.458	0.362	0.335
Austria	0.542	0.527	0.611	0.349	0.399	0.493	0.536	0.507	0.617	0.729	0.754
Czech Republic	0.602	1.000	0.473	0.270	0.253	0.277	0.308	0.258	0.287	0.218	0.329
Denmark	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Finland	0.370	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	0.918	0.977	0.935	0.905	1.000	1.000	0.996	0.855	0.780
Italy	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.901	0.997
Japan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
South Korea	0.805	0.711	0.631	1.000	1.000	1.000	1.000	0.828	0.869	1.000	1.000
Netherlands	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Portugal	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Sweden	1.000	1.000	1.000	0.971	1.000	1.000	0.992	0.972	1.000	1.000	1.000
United Kingdom	1.000	1.000	1.000	0.911	0.764	0.800	0.809	0.690	0.729	0.804	0.880
United States	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 8
TFEEs for the non-metallic minerals industry.

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Australia	0.767	0.676	0.599	0.682	0.664	0.557	0.609	0.716	0.646	1.000	1.000
Austria	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.984
Czech Republic	0.815	0.814	0.782	0.826	0.801	0.844	0.698	0.622	0.818	0.792	1.000
Denmark	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Finland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Italy	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Japan	0.895	0.995	0.925	0.879	0.882	0.963	0.920	0.777	0.949	1.000	1.000
South Korea	0.644	0.663	0.625	0.644	0.700	0.751	0.699	0.652	0.626	0.613	0.594
Netherlands	1.000	0.971	0.891	0.987	0.936	0.906	0.899	0.866	0.916	0.876	0.962
Portugal	0.839	0.890	0.813	0.843	0.716	0.816	0.481	0.825	0.834	0.787	0.626
Sweden	1.000	0.826	1.000	1.000	1.000	1.000	0.997	0.802	1.000	0.966	0.987
United Kingdom	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United States	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 9
TFEEs for the paper industry.

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Australia	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.621	0.904
Austria	0.577	0.567	0.666	0.520	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Czech Republic	1.000	1.000	0.474	0.514	0.911	0.619	0.862	0.864	0.400	0.395	0.262
Denmark	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Finland	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Germany	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Italy	0.959	0.886	0.886	0.893	0.886	0.919	0.958	0.959	0.931	0.876	0.847
Japan	1.000	1.000	0.991	0.956	0.864	0.843	1.000	1.000	1.000	1.000	1.000
South Korea	0.662	0.479	0.533	0.489	0.546	0.564	0.568	0.307	0.318	0.214	0.314
Netherlands	0.936	0.918	0.940	0.984	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Portugal	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.132	0.155	0.144
Sweden	0.713	0.655	0.723	0.841	0.784	0.897	0.871	0.920	0.954	0.926	0.918
United Kingdom	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
United States	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

3. Methodology and data

3.1. DEA methodology

DEA is a linear programming method 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 is derived using the following linear programming problem, assuming variable returns to scale (VRS) proposed by Banker et al. [59]:

$$\text{Min}_{\theta,\lambda}\ \theta$$

$$\text{s.t.}\quad -y_i + Y\lambda \geqslant 0$$

$$\theta x_i - X\lambda \geqslant 0$$

$$e\lambda = 1$$

$$\lambda \geqslant 0, \tag{1}$$

where θ is a scalar that represents the efficiency score of the i-th DMU; e is an $1 \times \text{N}$ vector of ones; λ is an $\text{N} \times 1$ vector of constants; y_i is an $\text{M} \times 1$ output vector of DMU i; Y is an $\text{M} \times \text{N}$ output matrix composed of all output vectors of the N DMUs; x_i is a $\text{K} \times 1$ input vector of DMU i; and X is a $\text{K} \times \text{N}$ input matrix

Table 10
Benchmarks for inefficient Japanese industries.

Industry	Benchmark (peer ratio)
Chemical	2004: Netherlands (0.491), Germany (0.316), United States (0.192) 2005: Netherlands (0.433), Germany (0.401), United States (0.165)
Machinery	2003: Germany (0.775), United States (0.225) 2004: Sweden (0.707), United States (0.293) 2005: United States (0.789), Sweden (0.211)
Non-metallic Minerals	1995: Germany (0.558), United States (0.248), United Kingdom (0.194) 1996: Germany (0.653), United States (0.268), United Kingdom (0.078) 1997: Germany (0.555), United States (0.262), United Kingdom (0.184) 1998: United Kingdom (0.419), Germany (0.293), United States (0.288) 1999: United States (0.395), United Kingdom (0.379), Austria (0.226) 2000: United Kingdom (0.572), United States (0.34), Germany (0.088) 2001: United Kingdom (0.522), United States (0.277), Germany (0.201) 2002: United Kingdom (0.526), Germany (0.329), United States (0.145) 2003: Germany (0.622), United Kingdom (0.276), United States (0.102)
Paper	1997: Germany (0.839), United States (0.161) 1998: Germany (0.858), United States (0.142) 1999: Germany (0.627), United Kingdom (0.241), United States (0.132) 2000: United Kingdom (0.598), United States (0.223), Denmark (0.179)

composed of all input vectors of the N DMUs. The efficiency score satisfies $0 \leqslant \theta \leqslant 1$, which is a radial contraction coefficient for the inputs. If $\theta = 1$, DMU i operates on the efficiency frontier and is technically efficient. This is an input-oriented model in which the radial adjustment coefficient, θ, is multiplied by the input vector of DMU i. The constraint $e\lambda = 1$ is the convexity constraint to make the envelope the boundary of a minimum convex hull containing all DMUs within an industry in the same year. To control the industry and annual environment, all efficiency scores and input targets for DMU i in year t are determined by comparing them to the industry efficiency frontier in year t. That is, the DEA model uses observations from the same industry in the same year.

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

$$\text{Actual Energy Input}_{(i,j,t)} - [\text{Radial Adjustment}_{(i,j,t)} + \text{Non}-\text{radial Slack Adjustment}_{(i,j,t)}], \tag{2}$$

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 $(1-\theta)x_{(i,j,t)}$; the non-radial slack is defined as the amount of energy that can be reduced using the non-radial method. The TFEE index is defined as

$$\text{TFEE}_{(i,j,t)} = \text{Target Energy Input}_{(i,j,t)} / \text{Actual Energy Input}_{(i,j,t)}. \tag{3}$$

On the basis of the above definition, the TFEE assumes a value between zero and unity. Higher TFEEs imply greater energy efficiency, whereas a TFEE score of unity indicates that an industry is efficient and cannot save energy without reducing its value added. A TFEE score below unity implies that an industry is inefficient and can increase energy savings.

Table 11
Countries referencing Japan as a benchmark.

Industry	Benchmark (Number of Times)
Chemical	Italy (7), United Kingdom (3), Germany (1)
Construction	None
Food	Czech Republic (10), Australia (1), Germany (1), Italy (1), Sweden (1), United Kingdom (1)
Machinery	None
Metal	Germany (2), Italy (2), Austria (1)
Non-metallic Minerals	None
Paper	None

3.2. Data

Our annual dataset includes 10 industries in 14 developed countries for 1995–2005. Economic data are obtained from [26], a comprehensive database financed by the European Commission.[5] Energy data are obtained from [60], one of the most reliable sources of international energy statistics. Consumption of each energy source—e.g., coal, oil products, and natural gas—are changed from original units to their equivalent in tons of oil using specific conversion factors. The aggregated energy consumption may have the uncertainty of energy data by the conversion factors applied. But they are scrutinized by the experts of the International Energy Agency.

The EU KLEMS project [25] has developed a revolutionary, comprehensive database comprising European and other developed countries to analyze economic growth and productivity. This database facilitates international comparisons of industry-level efficiency.

Economic and energy-related data for various industries are then matched using the sources indicated above.[6] The countries in the database 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 construction; chemical and petrochemical; food and tobacco; iron, steel, and non-ferrous metals; machinery; non-metallic minerals; paper, pulp, and printing; textile and leather; transport equipment; and wood and wood products. Thus, the total number of industries is 140 (10 for each country). Table 1 presents details of the 10 industries. Because there are no energy data for four industries,[7] consistent annual data are available for 136 industries.

This model includes four inputs: labor, capital stock, energy, and non-energy intermediate inputs. Many international comparisons that use DEA adopt GDP as their output. However, this study calculates efficiency by industry. Since GDP indicates the total value added in each industry, we consider value added as the sole output. Monetary values are measured in euros, with 1997 as the base year, using purchasing power parity, also taken from [26]. Table 2 presents descriptive statistics of all variables.

[5] Although additional assumptions are inevitably imposed when constructing an industry-level economic data series, they are based on the standard economic growth theory. For more details, please visit the EU KLEMS website (http://www.euklems.net).

[6] Data for France and Belgium are not released in [26] because confidentiality had to be respected. See footnote 16 in [61].

[7] The following four industries were eliminated because energy consumption data are unavailable: transport equipment in Australia; transport equipment in Japan; wood and wood products in Japan; and textile and leather in Japan.

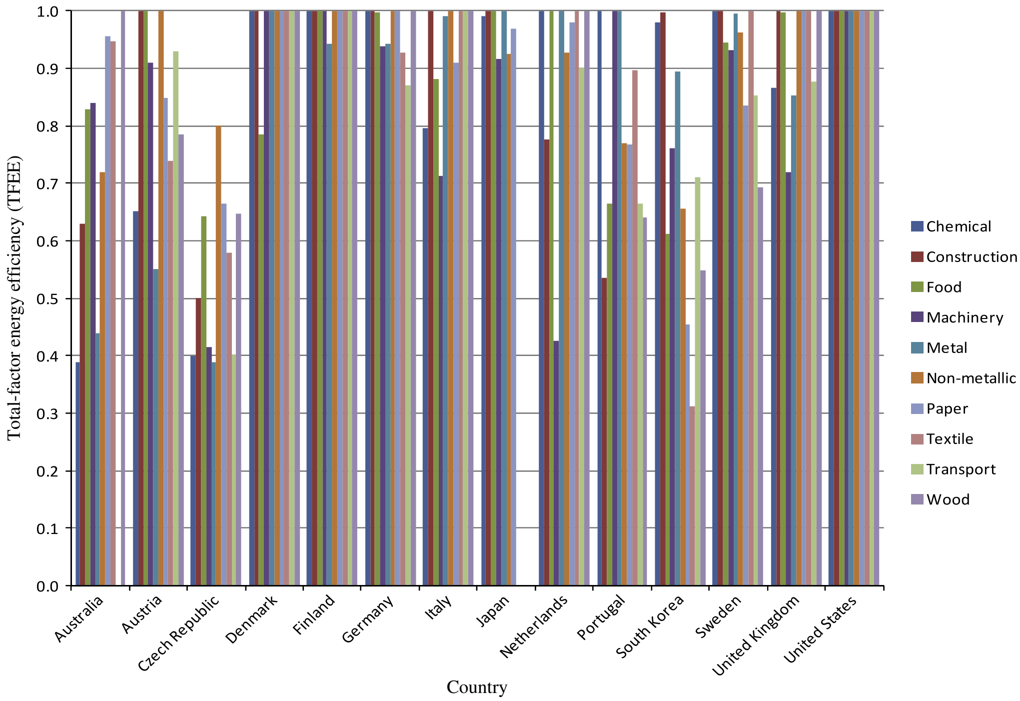

Fig. 1. Average TFEE per industry by country.

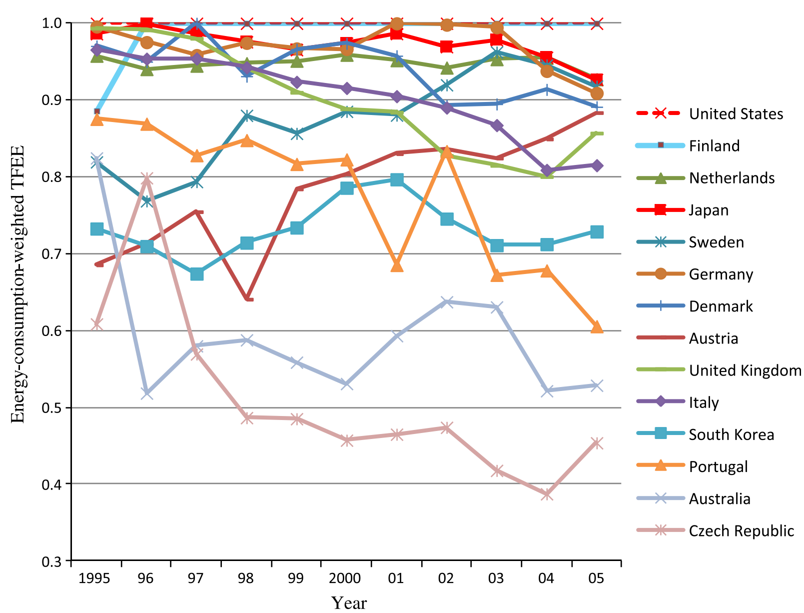

Fig. 2. Energy-consumption weighted total-factor energy.

4. Empirical results

4.1. Total-factor energy efficiency (TFEE)

To accommodate the varied structures of each industry examined, we calculate individual TFEEs. Tables 3–9 show the TFEE of seven industries.[8,9]

Let us examine TFEE results by industry. The chemical industry in six countries—Denmark, Finland, the Netherlands, Portugal, Sweden, and the United States—displays unvarying unity scores during the period and merits best practices among the sampled countries (Table 3). Australia, Austria, and the Czech Republic exhibit low efficiency TFEE scores for most years, implying inefficient operation.

The construction industry in Austria, Denmark, Finland, Germany, Italy, Japan, Sweden, the United Kingdom, and the United States operates efficiently (Table 4). South Korea consistently exhibits TFEE scores of unity except for in 2002. The Czech Republic, Portugal, and Australia present low TFEE scores in the initial surveyed years.

[8] We calculate data for 10 industries; however, owing to space limitations and the purpose of this study, we report results for only the seven industries for which Japanese data are available.

[9] Four countries show similar results in our study and in [41]: Australia, Japan, South Korea, and the United States. Efficiency rankings for these countries are similar in our results and in [41].

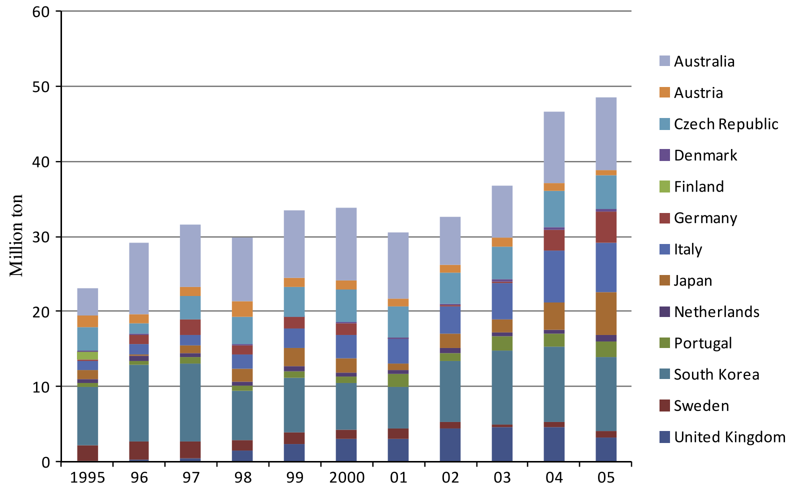

Fig. 3. Potential energy savings by country 1995–2005.

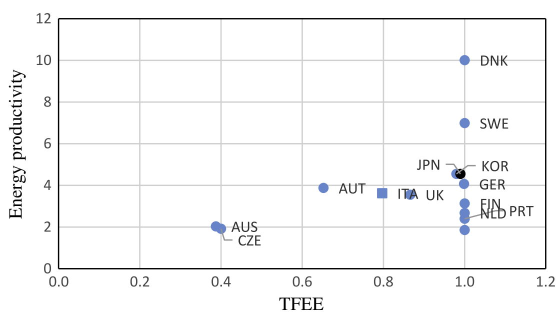

Fig. 4a. Average TFEE and energy productivity in the chemical industry 1995–2005. *Note:* Energy productivity in euros of value added per ton of oil equivalent.

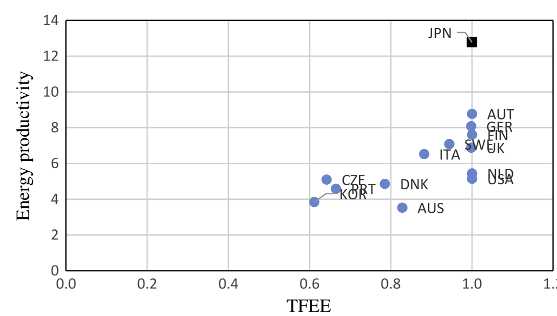

Fig. 4c. Average TFEE and energy productivity in the food industry 1995–2005. *Note:* Energy productivity in euros of value added per ton of oil equivalent.

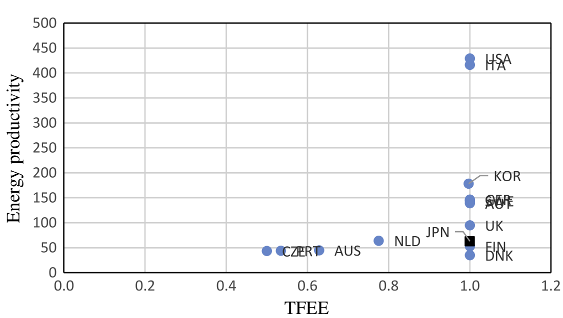

Fig. 4b. Average TFEE and energy productivity in the construction industry 1995–2005. *Note:* Energy productivity in euros of value added per ton of oil equivalent.

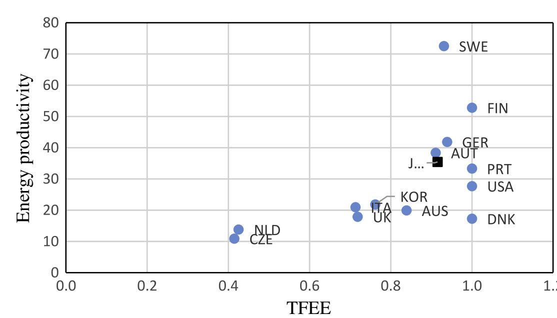

Fig. 4d. Average TFEE and energy productivity in the machinery industry 1995–2005. *Note:* Energy productivity in euros of value added per ton of oil equivalent.

The food industry in Austria, Finland, Japan, the Netherlands, and the United States exhibits TFEE scores at unity throughout the period. Australia, the Czech Republic, Portugal, and South Korea show low TFEE scores, below 0.5 (Table 5).

The machinery industry in Denmark, Finland, Portugal, and the United States exhibits TFEE scores of unity for all years. Austria, Germany, Japan, and Sweden show TFEE scores of unity for most sampled years (Table 6). The Czech Republic and the Netherlands exhibit low TFEE scores, some below 0.5. Italy's TFEE scores deteriorate from unity in the first three years to 0.246 at the end of the period.

The metal industry in Denmark, Japan, the Netherlands, Portugal, and the United States exhibits TFEE scores of unity during the period (Table 7). Australia, the Czech Republic, Finland, Germany, Italy, South Korea, Sweden, and the United Kingdom present mixed results, indicating efficient and inefficient years. Australia (except in 1995) and Austria present consistently low TFEE scores.

The non-metallic minerals industry in Denmark, Finland, Germany, Italy, the United Kingdom, and the United States displays consistent unity (Table 8). South Korea and Portugal register consistently low TFEE scores.

The paper industry in Denmark, Finland, Germany, the United Kingdom, and the United States exhibits TFEE scores of unity throughout the period (Table 9). TFEE scores for Austria and the Netherlands rise from 0.557 and 0.936, respectively, in 1995 to unity in 2005. In contrast, TFEE scores for the Czech Republic and

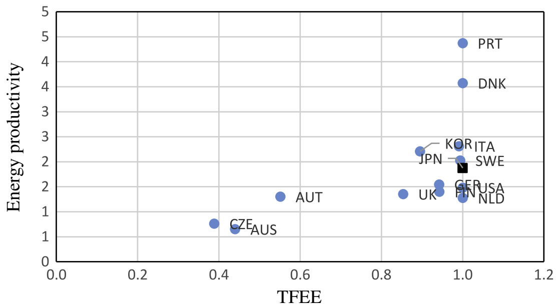

Fig. 4e. Average TFEE and energy productivity in the metal industry 1995–2005. *Note:* Energy productivity in euros of value added per ton of oil equivalent.

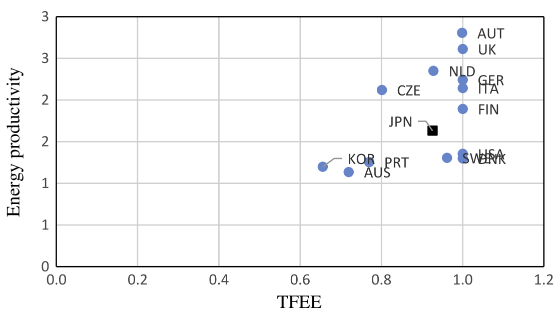

Fig. 4f. Average TFEE and energy productivity in the non-metallic minerals industry 1995–2005. *Note:* Energy productivity in euros of value added per ton of oil equivalent.

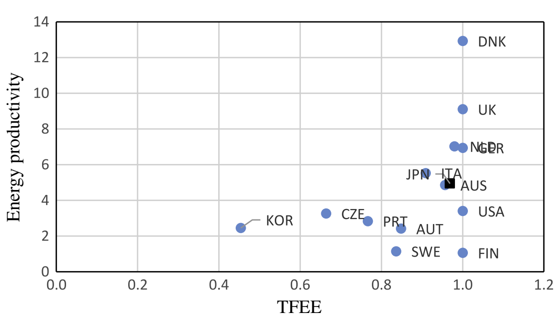

Fig. 4g. Average TFEE and energy productivity in the paper industry 1995–2005. *Note:* Energy productivity in euros of value added per ton of oil equivalent.

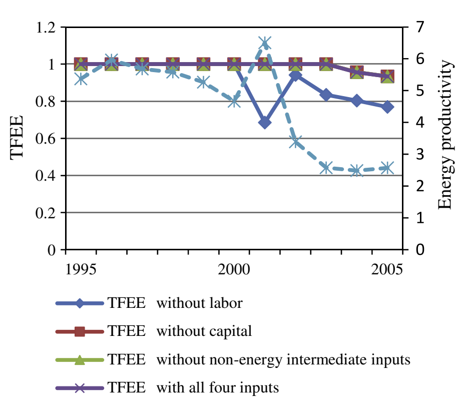

Fig. 5a. TFEEs in Japan's chemical industry 1995–2005.

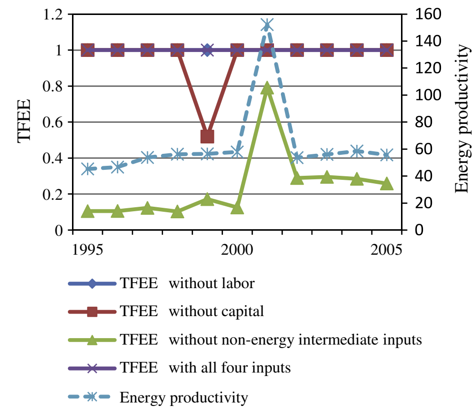

Fig. 5b. TFEEs in Japan's construction industry 1995–2005.

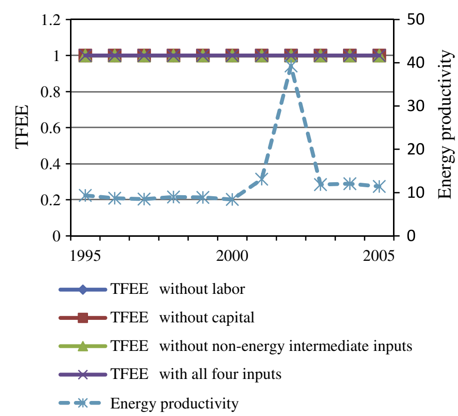

Fig. 5c. TFEEs in Japan's food industry 1995–2005.

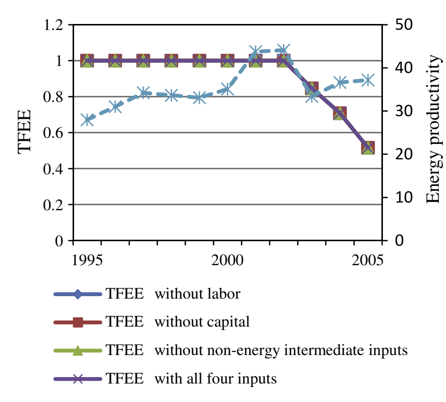

Fig. 5d. TFEEs in Japan's machinery industry 1995–2005.

Portugal deteriorate drastically from unity in 1995 to 0.262 and 0.114, respectively, in 2005.

Now we examine Japan's energy efficiency for the seven industries on the basis of results shown in Tables 3–9. Japan's construction, food, and metal industries maintain TFEEs at unity, indicating that they operated at the efficiency frontier throughout the period. However, Japan's chemical, machinery, non-metallic minerals, and paper industries display inefficient TFEEs below unity for several years within the period. Japan's non-metallic minerals industry became efficient only in the final two years studied. However, efficiency in its chemical and machinery industries worsened after 2004 and 2003, respectively.

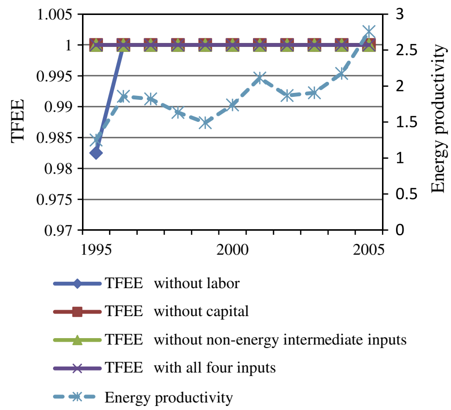

Fig. 5e. TFEEs in Japan's metal industry 1995–2005.

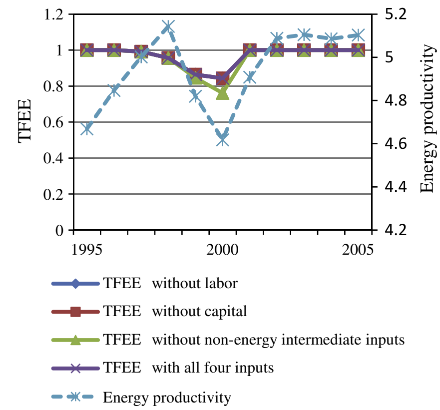

Fig. 5g. TFEEs in Japan's paper industry 1995–2005.

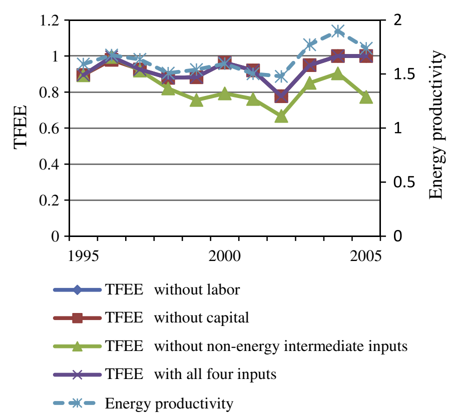

Fig. 5f. TFEEs in Japan's non-metallic minerals industry 1995–2005.

Japan's paper industry was inefficient only from 1997 to 2000. In sum, Japan's chemical, machinery, non-metallic minerals, and paper industries used energy inefficiently in some sampled years. Apart from in the machinery industry in 2004 and 2005, however, potential for energy-saving in these industries was at most 20%.

In general, a small number of efficient DMUs can drastically affect the efficiency frontier in DEA. Slight variation in a specific DMU's position relative to other DMUs may change its status from inefficient to efficient and vice versa [62]. Fluctuations in the metal industry, for example, are observed in some countries during some years (e.g., Australia in 1995–1996, the Czech Republic in 1995–1997, Finland in 1995–1996, and South Korea in 1997–1998). Because data for each industry are available for 14 countries, the annual industry efficiency frontier position can change significantly with a change in the status of a specific country. Similar fluctuations appear in other industries, albeit less frequently than in the metal industry.

We evaluate an inefficient TFEE score on the basis of efficient DMUs as benchmarks (reference sets), which are useful references for inefficient DMUs. Table 10 presents the benchmark countries for Japan's inefficient industries. The weighted input combination from the ratios in parentheses indicates the point used to evaluate the radial efficiency of Japanese industries. Inefficiency removal is accomplished by contracting the actual inputs to a linear combination by the ratios whereby input slacks reduce to zero (if they occur). Thus, the benchmarks and ratios provide the corresponding inefficient industry with an indication of improved energy efficiency. Germany, the United Kingdom, and the United States frequently appear as benchmarks in Table 9; especially, the United States is a benchmark for inefficient countries. Japan can benefit from implementing energy-saving technologies utilized by these countries.

Japan is known to have efficient DMUs by the standards of inefficient countries. Table 11 shows countries with inefficient industries that consider Japan as one of their benchmarks for the years in which the corresponding Japanese industry is efficient. As per the table, Japan's food industry is the benchmark 10 times for the Czech Republic and once for each of the five other countries. Furthermore, Japan's chemical and metal industries are benchmarks for certain countries. However, Japan's construction, machinery, non-metallic minerals, and paper industries are never benchmarks for any country during the period, implying that these four industries hold singular positions along efficiency frontiers in their respective industries.

4.2. International comparison of energy efficiency and energy-savings potential

Fig. 1 presents average TFEEs of each industry in the 14 countries for 1995–2005. First, average TFEEs of all industries in the United States stand at unity, implying that the United States operated efficiently in all industries during the period and had the best technology and production processes. Denmark (except for its food industry) and Finland (except for its metal industry) display perfect average TFEE scores. The Czech Republic, South Korea, and Australia (except for its wood industry) display no industries with average TFEE scores of unity. Many industries in these three countries exhibit lower average TFEEs, implying that significant amounts of energy can be conserved.

Tables 3–9 show mixed results for Japan. Even though Japan exhibits perfect average TFEEs in the construction, food, and metal industries, average TFEEs are below unity but above 0.9 for the chemical, machinery, non-metallic minerals, and paper industries.

Next, we examine energy efficiency by country. Fig. 2 shows energy-consumption-weighted TFEEs. Because energy consumption in each industry varies widely within a country, we disregard simple average TFEEs for the countries and present energy-consumption-weighted TFEEs.[10] Japan's weighted TFEE decreases marginally from 0.986 in 1995 to 0.927 in 2005. As Fig. 2 shows, the three lowest-ranking countries in 2005 (the Czech Republic, Australia, and Portugal) suffer from falling energy efficiency during the period. In contrast, the relatively efficient

[10] Note that the energy-consumption-weighted TFEE is obtained by using the available industry TFEE scores. Japan's score is computed using the seven available industries, whereas other countries' scores, except Australia's, are calculated using all 10 available industries.

countries with average values exceeding 0.9 in 2005 include Finland, Germany, Japan, the Netherlands, Sweden, and the United States. It is noteworthy that the United States and Finland exhibit efficiency across all industries during the period (except in 1995).

How much energy consumption can each country reduce without simultaneous reductions in economic output? Fig. 3 shows potential energy savings by country. Note that potential energy savings of each industry are given by the sum of radial and non-radial slack adjustments. Potential energy savings of each country in Fig. 3 are calculated by summing all potential energy savings of each industry in that country.

In 1995, South Korea had the greatest potential for energy savings, followed by Australia and the Czech Republic. In 2005, three countries—South Korea, Australia, and Italy—shared the greatest potential for energy savings. Japan accounted for 5.4% of the potential energy savings of the 14 countries in 1995 and witnessed a growth of 11.7% in 2005.

4.3. TFEE comparisons with EP

As indicated, scholars have traditionally used EP—energy consumption per output—as an index of energy efficiency. Nevertheless, that measure disregards the substitutability of inputs. Figs. 4a–4g compare Japan's average TFEE position to average EP during the period. Differences in rankings between the two indexes arise from whether other inputs are considered when measuring efficiency.

Correlation coefficients of the two indexes in the seven industries range from 0.348 for the construction industry to 0.593 for the metal industry. Only Japan's food industry attains first place in both indexes. When other inputs are ignored in measuring efficiency, the EPs of Japan's construction and metal industries are moderate, but they attain full TFEE scores when other inputs are considered. Although Japan attains high average TFEE scores exceeding 0.9 for the machinery, non-metallic minerals, and paper industries, average EPs are low.

4.4. Sensitivity analyses

We conduct sensitivity analyses to ensure the robustness of these TFEE results. Because DEA is a non-parametric method, we cannot statistically verify whether a variable should be included in the analysis. We recalculate the annual TFEE of each industry using the remaining observations in which one input except energy is removed.[11] Figs. 5a–5g compare the results with the original TFEE. Except for the construction industry, all TFEE results obtained by dropping one input exhibit the same direction as the ordinary TFEEs.[12]

We also compare Japan's TFEE results with a conventional partial factor EP index. EP, a traditional energy efficiency index, is defined as value added divided by energy consumption. Whereas all inputs are taken into account in TFEE, energy is the sole input in EP. Each industry's EP is indicated along the right axis of Figs. 4a–4g. The same tendency as that between the original TFEE and EP is observed in the chemical, non-metallic minerals, and paper industries. On the other hand, EP values in the construction, food, machinery, and metal industries significantly diverge from their TFEEs. The divergence stems from the difference between total-factor and partial-factor frameworks.

[11] We thank anonymous referees for the suggestion on this point.

[12] Divergence between TFEE without non-energy intermediate inputs and others is observed in other countries. We surmise that this is a result of peculiarities in the construction industry.

5. Conclusion

This study compares Japan's industry-level energy efficiency with that of other developed countries. We analyze TFEE and potential energy savings of 10 industries in 14 developed countries for 1995–2005 using the DEA approach. For robustness, we conducted sensitivity analyses and comparisons with EP.

Even though several Japanese industries were benchmarks for less energy-efficient countries and DMUs during 1995–2005, our in-depth analysis indicates further potential for energy consumption savings within Japan's industrial sectors. Japan's construction, food, and metal industries display efficient TFEE scores throughout the period. However, its chemical, machinery, non-metallic minerals, and paper industries show inefficient TFEE scores in some years. The non-metallic minerals industry in particular became efficient within the final two years sampled. Overall, Japan's weighted TFEE declines slightly from 0.986 in 1995 to 0.927 in 2005.

Benchmarking countries provides useful information about improving energy efficiency among inefficient industries. Germany, the United Kingdom, and the United States frequently appear as benchmarks for inefficient Japanese industries. The United States consistently appears as a benchmark for each Japanese industry examined in this study.

Our study presents several policy implications. First, to improve inefficient industries, Japan should adopt energy conservation technologies employed in benchmark countries. We also find that Japan's efficient industries are benchmarks for other countries, such as Italy's chemical industry and the Czech Republic's food industry. Japan can provide energy-saving technologies to these countries.

Three suggestions for future research emerge from these findings. First, this study compares energy efficiency across countries by industry but does not analyze factors contributing to inefficiency. Because disaggregated industry-level economic and energy data are insufficient for this analysis, future research can regress energy efficiency scores on control variables of aggregated country-level data. Second, because this study considers only manufacturing, future research can extend the analysis to non-manufacturing industries. Third, we treat energy measured in tons of oil as one equivalent input; however, aggregating energy sources inevitably raises questions about how differences in substitutability and cost among energy sources are managed [12]. Therefore, improving energy input measurement will be a constant goal for the future.

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