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International comparison of energy efficiency of fossil power generation

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Abstract

The purpose of this study is to compare the energy efficiency of fossil-fired power generation for Australia, China, France, Germany, India, Japan, Nordic countries (Denmark, Finland, Sweden and Norway aggregated), South Korea, United Kingdom and Ireland, and United States. Together these countries generate 65% of worldwide fossil power generation. Separate benchmark indicators are calculated for the energy efficiency of natural gas, oil and coal-fired power generation, based on weighted-average energy efficiencies. These indicators are aggregated to an overall benchmark for fossil-fired power generation. The weighted average efficiencies are 35% for coal, 45% for natural gas and 38% for oil-fired power generation.

The Nordic countries, Japan and United Kingdom and Ireland are found to perform best in terms of fossil power generating efficiency and are, respectively 8%, 8% and 7% above average in 2003. South Korea and Germany are, respectively 6% and 4% above average and the United States and France are, respectively 2% and 4% below average. Australia, China and India perform 7%, 9% and 13%, respectively below average.

The energy savings potential and CO_2 emission reduction potential if all countries produce electricity at the highest efficiencies observed (42% for coal, 52% for natural gas and 45% for oil-fired power generation), corresponds to 10 EJ and 860 Mtonne CO_2, respectively.

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1. Introduction

International comparisons of energy efficiency can provide a benchmark against which a country's performance can be measured against that of other countries. The results can be used to determine potential energy savings and greenhouse gas emission reduction potentials.

Energy-efficiency analyses for power generation on a country level have been performed in the past, but few recent studies are available. Furthermore benchmarks for overall fossil-fired power generation are not available.

This analysis aims to make a comparison of the efficiency of fossil-fired power generation (coal, oil and natural gas). For this purpose, specific benchmark indicators are developed for natural gas, oil and coal-fired generation efficiencies. These indicators are aggregated to a benchmark for fossil-fired generation efficiency.

The countries evaluated in this study are Australia, China,[1] France, Germany, India, Japan, Nordic countries (Denmark, Finland, Sweden and Norway aggregated), South Korea, United Kingdom and Ireland, and United States. Together these countries generate 65% of worldwide fossil power generation.

The energy efficiencies calculated in this analysis are based on IEA statistics. For all countries checks are made with available national statistics. The results of this are given in the Appendix. In some cases IEA statistics are replaced by national statistics.

This paper is structured as follows. Section 2 describes the used methodology. Section 3 gives the fuel mix for power generation in 2003 and the development of fossil power generation for the period 1990–2003. Section 4 shows the results of the study. First the efficiency of coal, natural gas and oil-fired power generation is given, followed by the benchmark indicators for fossil-fired power

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generation. Section 5 discusses uncertainties in this analysis and Section 6 gives the conclusions.

2. Methodology

This section gives an overview of the methodology applied and discusses input data used for the study.

The methodology used in this study to calculate the energy efficiency of power generation is based on the "Handbook of International Comparisons of Energy Efficiency in the Manufacturing Industry" (Phylipsen et al., 1998). Formula (1) gives the energy efficiency of power generation

$$E = (P + H \times s)/I, \tag{1}$$

where E is the energy efficiency of power generation, P the power production from public power plants and public CHP plants, H the heat output from public CHP plants, $s = 0.175$, correction factor between heat and electricity, defined as the reduction in electricity production per unit of heat extracted and I the fuel input for public power plants and public CHP plants.

The correction factor for heat extraction reflects the amount of electricity production lost per unit of heat extracted from the electricity plant(s). For district heating systems, the substitution factors vary between 0.15 and 0.2. Here 0.175 is used.

To determine the efficiency for power production for a region, we calculate the weighted average efficiency of the countries included in the region.

2.1. *Benchmark for fossil generation efficiency*

In this analysis we compare the efficiency of fossil-fired power generation across countries and regions. Instead of simply aggregating the efficiencies for different fuel types to a single efficiency indicator, we determine separate benchmark indicators per fuel source. This is because the energy efficiency for natural gas-fired power generation is generally higher than the energy efficiency for coal-fired power generation, while the choices for fuel types are often outside the realm of the industry. Choices for fuel diversification have in the past often been made at the government level for strategic purposes, e.g. fuel diversification and fuel costs.

A method for benchmarking energy efficiency is the comparison of countries' efficiencies against average efficiencies. This method allows to estimate the difference to the overall average efficiency given a country's specific fuel mix. The average efficiency is calculated per fuel source and per year and is weighted by power generation output.

Formula (2) gives the weighted average efficiency for coal-fired power generation (BC) as an example:

$$\mathrm{BC} = \sum(\mathrm{PC}_i + \mathrm{HC}_i \times s)/\sum \mathrm{IC}_i, \tag{2}$$

where BC is the benchmark efficiency of coal. This is the weighted average efficiency of coal-fired power generation for the selected countries, PC_i the coal-fired power production for country or region $i (i = 1, \ldots, n)$, HC_i the heat output for country or region $i (i = 1, \ldots, n)$, s the correction factor between heat and electricity, defined as the reduction in electricity production per unit of heat extracted and IC_i the fuel input for coal-fired power plants for country or region $i (i = 1, \ldots, n)$.

To determine the performance of a country relative to the benchmark efficiency we divide the efficiency of a country for a certain year by the benchmark efficiency in the same year. Formula (3) gives the indicator for the efficiency of coal-fired power as an example:

$$\mathrm{IC}_i = \mathrm{EC}_i/\mathrm{BC}, \tag{3}$$

where IC_i is the benchmark indicator of the energy-efficiency of coal-fired power generation for country or region i.

Countries that perform better than average for a certain year show numbers above 100% and vice versa.

To come to an overall comparison for fossil-fired power efficiency we calculate the output-weighted average of the three indicators, as is shown in formula (4)

$$\mathrm{IF}_i = \frac{\mathrm{IC}_i \times \mathrm{PC}_i + \mathrm{IG}_i \times \mathrm{PG}_i + \mathrm{IO}_i \times \mathrm{PO}_i}{\mathrm{PC}_i + \mathrm{PG}_i + \mathrm{PO}_i}, \tag{4}$$

where IF_i, IC_i, IG_i and IO_i, are respectively the benchmark indicator for the energy-efficiency of fossil-fired, coal-fired, gas-fired and oil-fired power generation for country or region i; PC_i, PG_i and PO_i, are respectively the coal-fired, gas-fired and oil-fired power production for country or region i.

2.2. *Input data*

This analysis is based on data from IEA Energy Balances edition 2005. Data in IEA Energy Balances is given in net calorific value (NCV).[2] Please note that efficiencies based on gross calorific value are lower. The difference is around 10% for natural gas, 3% for coal and 7% for oil. Power generation in IEA data is given as gross power generation. This refers to the electric output of the generator. Net electricity output refers to the electric output minus electrical power used in a plant's auxiliary equipment such as pumps, motors and pollution control devices. This means the calculated energy efficiencies in this analysis do not refer to actual net electricity output. This especially influences the energy efficiency of coal-fired power plants. Power used for auxiliary equipment is around 6–8% for coal-fired power plants and 2–3% for natural gas-fired power plants.

In this study, we take into account public power plants and public CHP plants. Power generation by autoproducers is not taken into account. Worldwide the power generation of autoproducers accounts for 6% of total power generation in 2003. Some countries have a relatively high share of power generation by autoproducers, such as Finland 21%, Japan 12%, India 11% and United Kingdom 10%.

[2] The net calorific value (NCV) or lower heating value (LHV) refers to the quantity of heat liberated by the complete combustion of a unit of fuel when the water produced is assumed to remain as a vapour and the heat is not recovered.

We distinguish three types of fuel sources: coal and coal products, crude oil and petroleum products and natural gas. We will refer to these fuel sources as coal, oil and gas, respectively.

As a check, IEA statistics are compared to available national statistics. In some cases energy efficiencies based on IEA statistics are replaced by energy efficiencies calculated from national statistics. This is done when the efficiencies based on national statistics seem more reliable. Information about the statistics that are used for the analysis can be found in the Appendix.

3. Fuel mix and power generation

Figs. 1 and 2 show the fuel mix for public electricity production in 2003 based on electricity output.

The share of fossil fuels in the overall fuel mix for electricity generation is in general more than 50–60%. Two exceptions are France, which has a large share of nuclear power (84%), and the Nordic countries, which use a lot of hydropower (50%).

From the fossil fuels, coal is most frequently used. The share of oil-fired power generation is limited; only Japan and the United States have larger amounts, in absolute sense.

Figs. 3, 4, 5 and 6 show the amount of coal, gas, oil and total fossil-fired power generation, respectively in the period 1990–2003, from public power plants and public CHP plants. Note that the scales of the figures are different.

4. Results

4.1. Efficiency of coal, gas and oil-fired power generation

Figs. 7, 8 and 9 show the efficiency trend for coal, gas and oil-fired power production, respectively, for the period

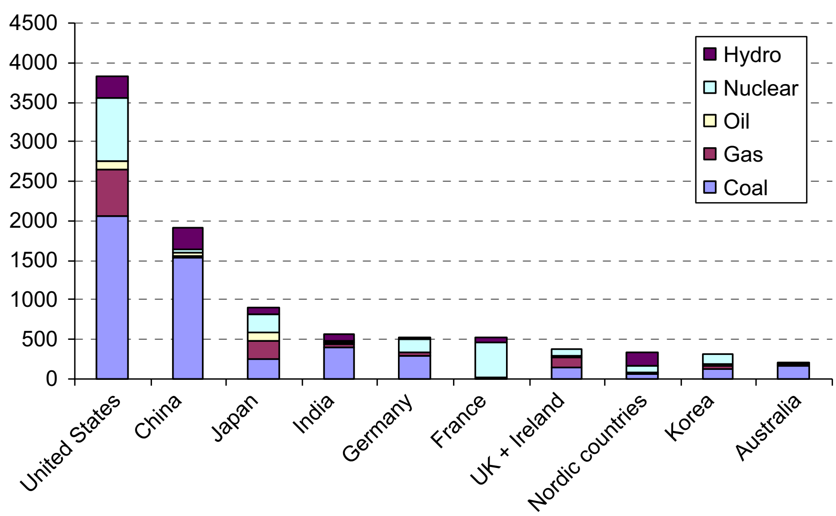

Fig. 1. Public power generation by source in 2003 in TWh (IEA, 2005b).

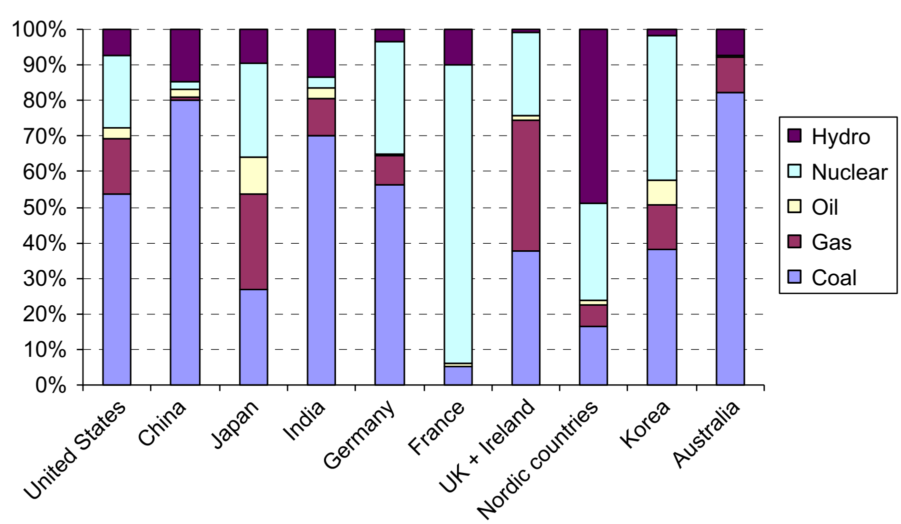

Fig. 2. Relative public power generation by source in 2003 (IEA, 2005b).

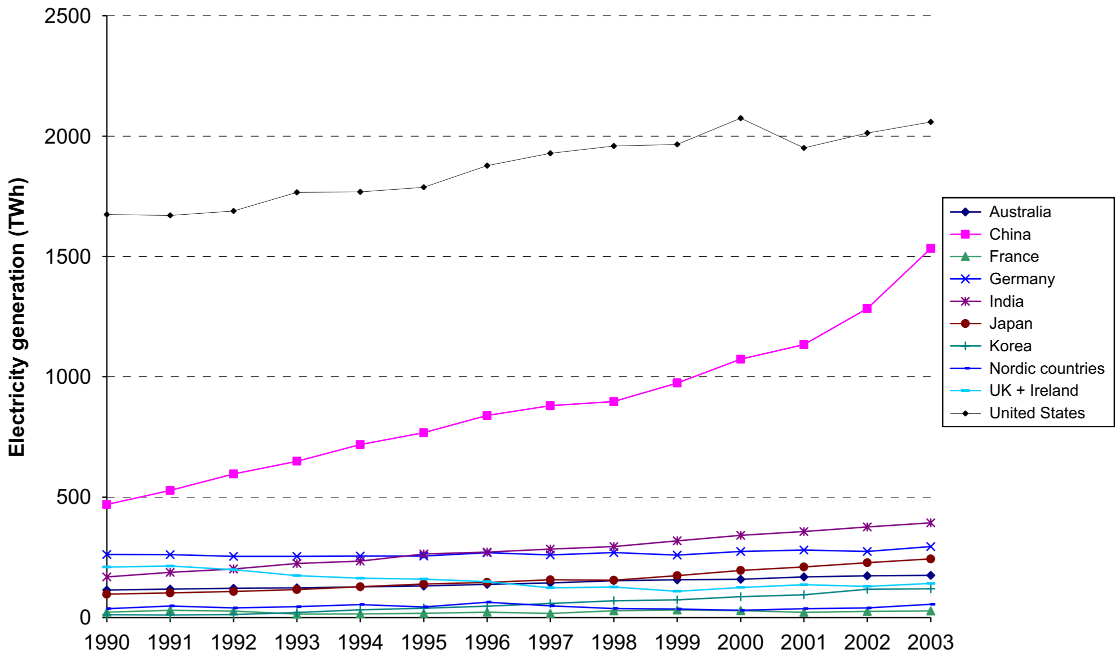

Fig. 3. Coal-fired power generation.

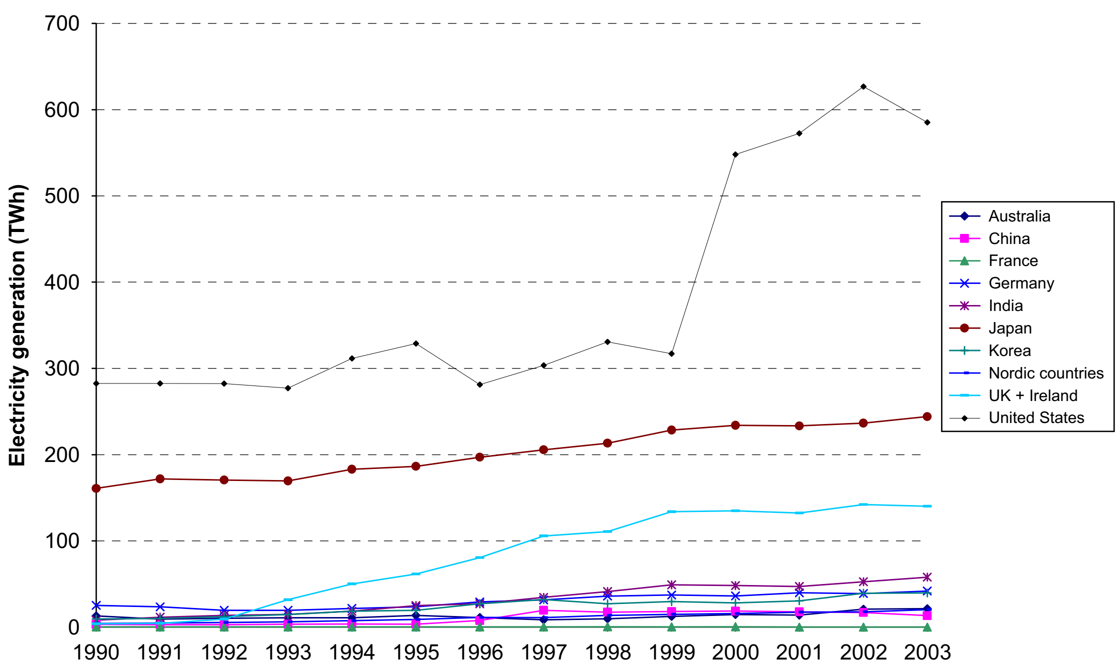

Fig. 4. Gas-fired power generation (natural gas-fired power generation capacity increased in the United States from 75 GW in 1999 to 210 GW in 2003 (US DOE, 2006).

1990–2003. Fig. 10 shows the energy efficiency of fossil-fired power generation by the weighted-average efficiency of gas-, oil- and coal-fired power generation.

The energy efficiencies for coal-fired power generation range from 30% for India to 42% for Japan in 2003. The average efficiency of the countries is 37% and the weighted average efficiency is 35% in 2003.

For gas-fired power generation, the efficiencies range from 39% for Australia to 52% for India in 2003. The average efficiency for gas is 46% and the weighted average efficiency is 45% in 2003.

For oil-fired power generation, the efficiencies range from 30% for India to 45% for Japan in 2003. The average efficiency for oil is 37% and the weighted average efficiency is 38% in 2003.

For overall fossil-fired generation, the efficiencies range from 32% for India to 43% for United Kingdom and Ireland and Japan in 2003. Below we discuss the results by country.

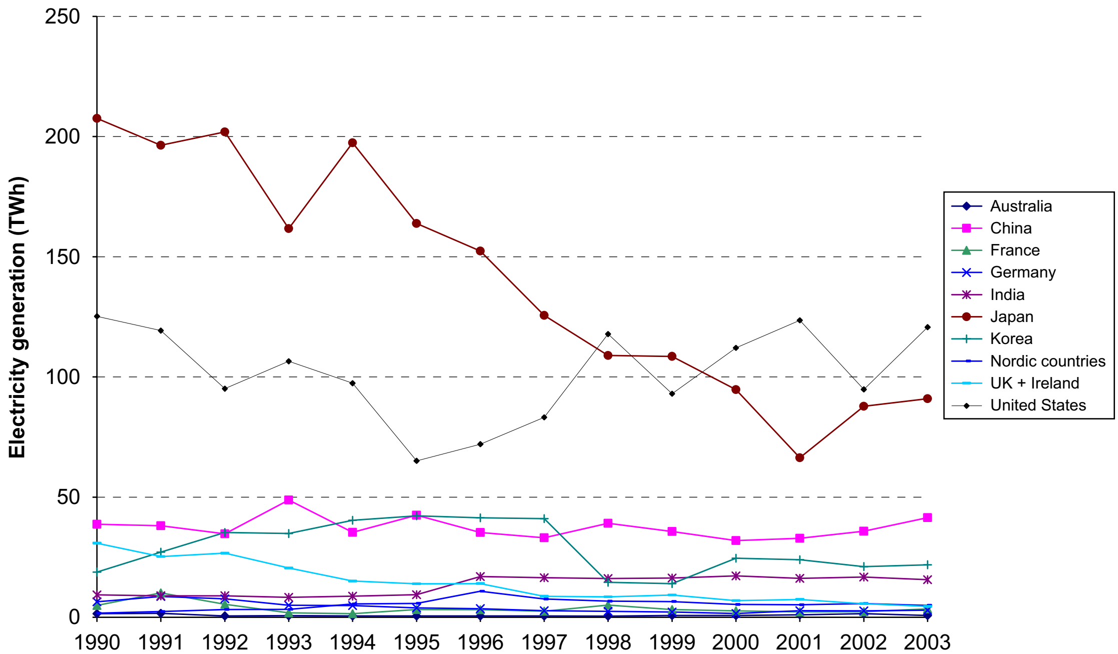

Fig. 5. Oil-fired power production.

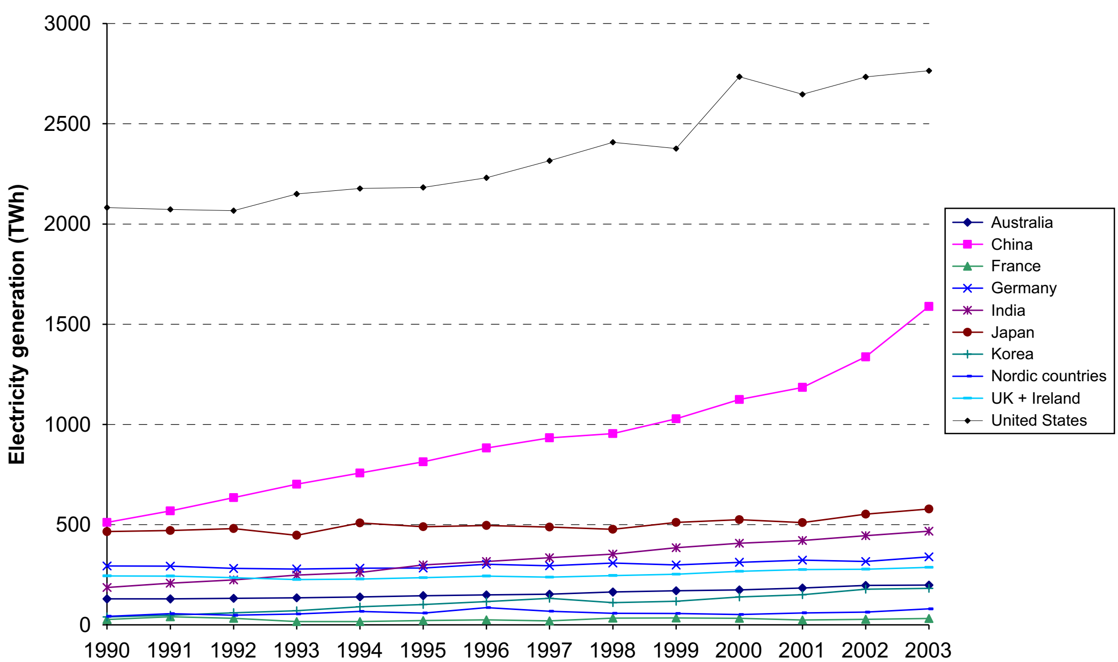

Fig. 6. Fossil-fired power production.

4.1.1. Australia

Total fossil-fired power generation in Australia is 198 TWh in 2003, of which 90% is generated from coal.

The energy efficiency for coal-fired power generation is fairly constant in the period 1990–2003, at 35%.

The energy efficiency of gas-fired power generation shows a strong peak in 2000 of 52%, possibly due to data unreliability. The energy efficiency in 2003 is 39%. Gas-fired power generation is 21 TWh in 2003.

Oil-fired power generation in Australia is very low, only 1 TWh in 2003.

4.1.2. China

China is the second largest fossil-fired power generator of the included countries and generates 1588 TWh in 2003, of which 97% is generated by coal.

The energy efficiency of coal-fired power generation increased from 31% in 1998 to 33% in 2002. Coal-based

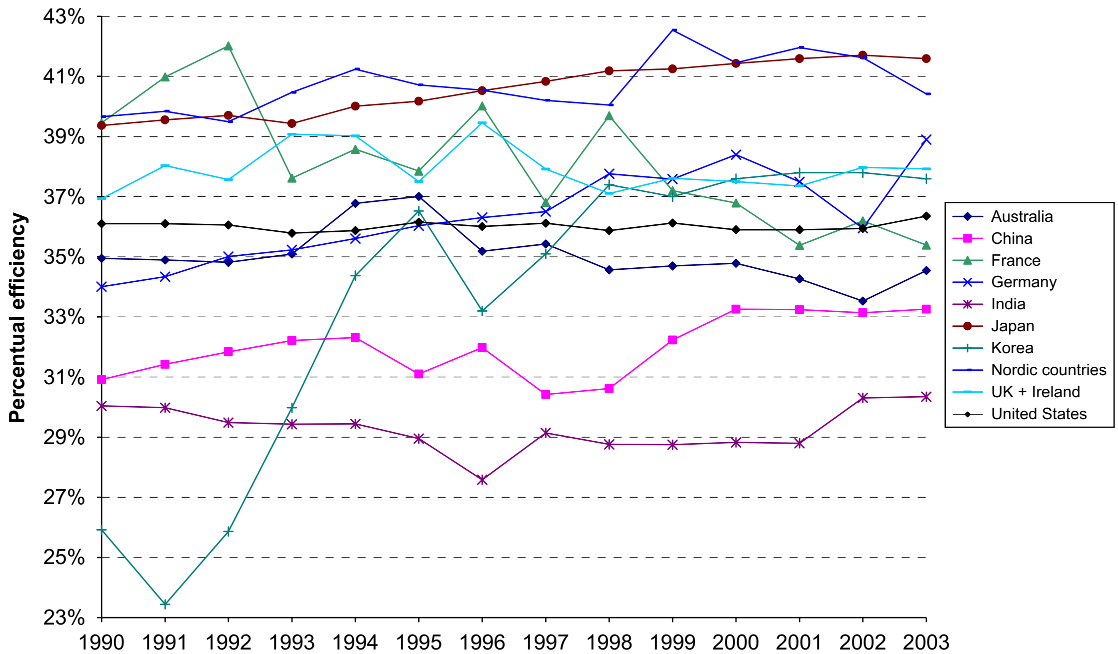

Fig. 7. Efficiency of coal-fired power production.

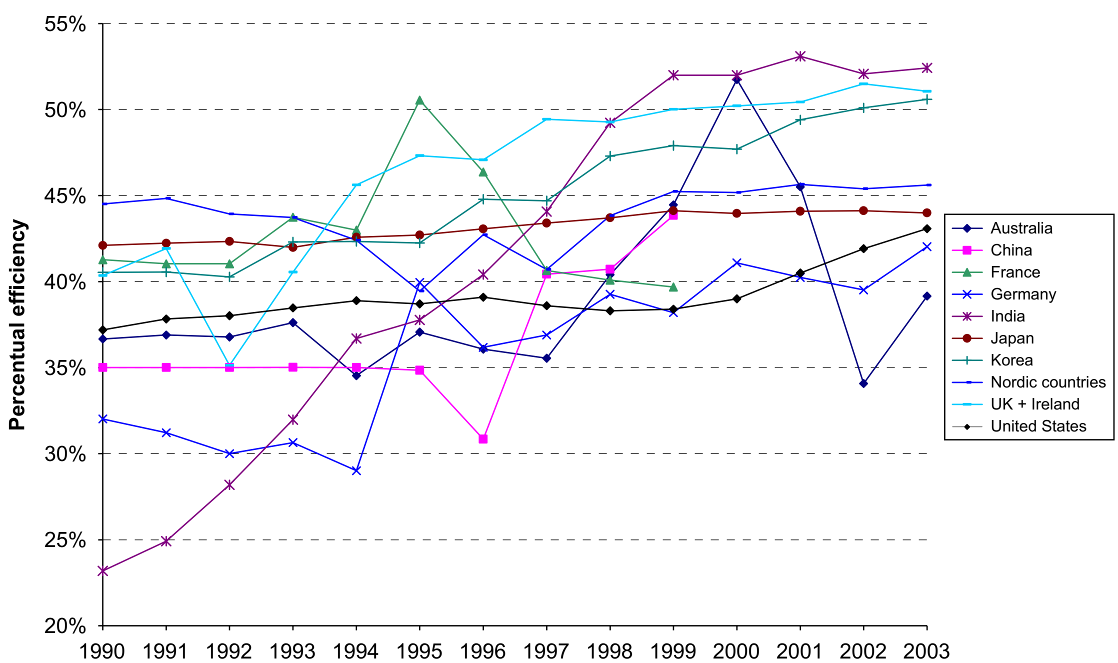

Fig. 8. Efficiency of gas-fired power production.

electricity production increases strongly from 898 TWh in 1998 to 1533 TWh in 2003.

Fig. 8 shows an increase of efficiency of gas-fired power generation for China from 35% in the period 1990–1995 to 44% in 2003. This is a substantial increase in energy efficiency. Gas-fired power generation increased from 3 TWh in the period 1990–1995 to 13 TWh in 2003. In 1996, the first units of a 2500 MW combined cycle gas turbine (CCGT) power plant came online in Hong Kong, all units of the plant were completed in 2004 (Power Technology, 2004).

Oil-fired power generation is 41 TWh in 2003. The energy efficiency of oil-fired power generation is constant in the period 1990–2003, at 34%.

4.1.3. France

Fossil-fired power generation in France is fairly small, only 31 TWh in 2003. This is mainly generated by coal.

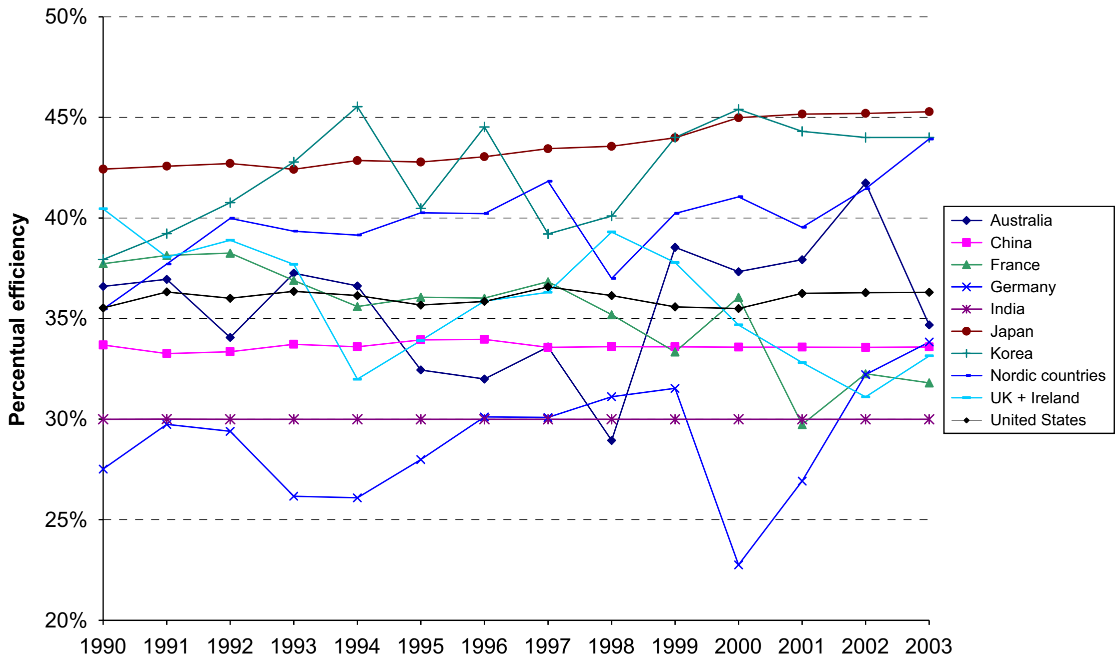

Fig. 9. Efficiency of oil-fired power production.

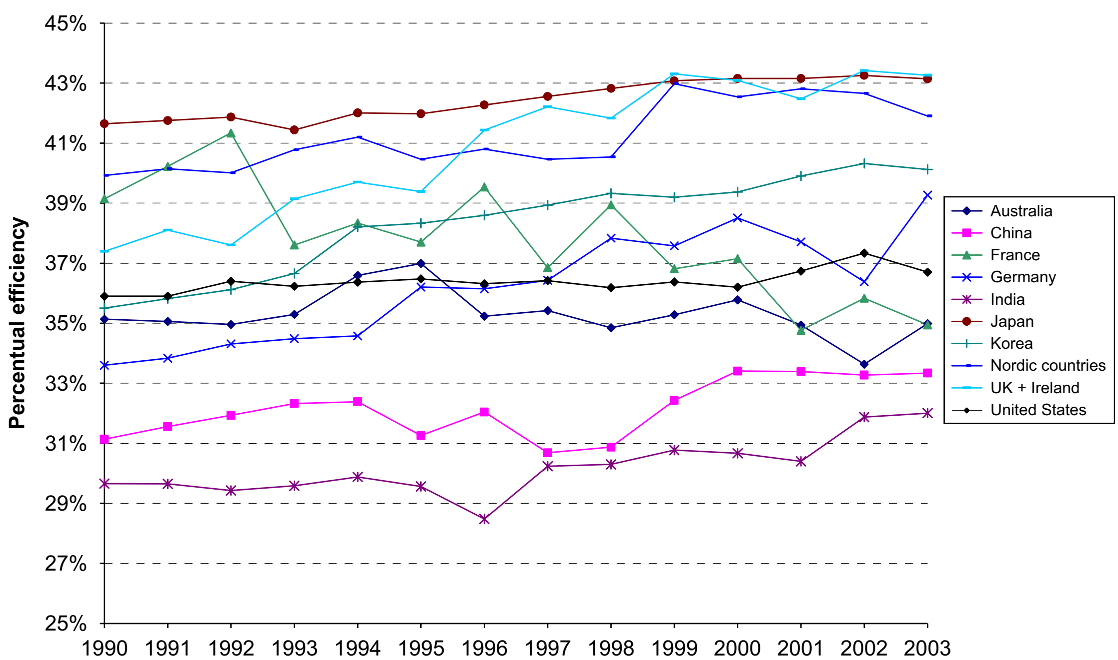

Fig. 10. Weighted average efficiency of fossil-fired power production.

There is no gas-fired power generation by public power plants in France, according to IEA statistics. Oil-fired power generation is only 4 TWh.

The energy efficiency for coal-fired power plants in France ranges from 35% to 40%. Coal-fired power generation in France shows strong fluctuations year by year ranging from 15 to 31 TWh. This means that the capacity factor of coal-fired power plants varies strongly which generally reduces energy efficiency.

4.1.4. Germany

Fossil-fired power generation in Germany is 340 TWh in 2003, of which 87% is produced from coal.

After the reunification of West and East Germany several lignite power plants were closed. This led to a higher efficiency of coal-fired power generation, from 34% in 1990 to 39% in 2003. The IEA statistics show a 7% lower share of lignite-based power production in 1990 than in the year before. In the period 1990 to 2000, the production of lignite-based electricity decreased by 14%. Hard coal-based power production increased by 25% between 1989 and 2000.

In the mid-1990s, the natural gas market was liberalised in Germany, leading to more competition and lower gas prices. This resulted in more gas use and a large increase of CHP capacity. This has resulted in a strong increase of efficiency of gas-based power generation from 29% in 1994 to 42% in 2003, as shown in Fig. 8. Gas-fired power generation increased from 22 TWh in 1994 to 42 TWh in 2003.

Oil-fired power generation in Germany is very small, only 3 TWh in 2003.

4.1.5. India

Fossil-fired power generation in India is 468 TWh in 2003, of which 84% is produced from coal. Total coal-fired capacity in India, excluding auto-producers, is 62 GW in 2002 (TERI, 2004).

The energy efficiency for coal-fired power generation is low, 30%. Some reasons for this may be that the coal is unwashed, has a high ash content of 30–55%, and coal-fired capacity is used for peak load power generation as well as base load power generation (IEA, 2003b).

The energy efficiency for gas-fired power generation is high, 52% in 2003. Gas-fired capacity in India is about 11 GW in 2002 (TERI, 2004). Gas-fired power plants in India are fairly new and all built in the last 15 years. Gas-fired power generation increased from 8 TWh in 1990 to 58 TWh in 2003. Many gas-fired power plants in India use CCGT technology (IEA, 2003b).

4.1.6. Japan

Japan is the third largest fossil-fired power producer of the included countries with 578 TWh in 2003. Of this amount, 244 TWh is generated by gas, 243 TWh by coal and 91 TWh by oil.

Fig. 3 shows an increase of coal-fired power generation in Japan from 97 TWh in 1990 to 243 TWh in 2003. The energy efficiency increases in this period from 39% in 1990 to 42% in 2003.

Fig. 8 shows an increase of gas-fired generating efficiency in Japan from 42% in 1990 to 44% in 2003. Gas-based electricity generation increased in this period from 161 to 244 TWh, as shown in Fig. 4. Out of a total natural gas capacity in 2000 of 56 GW, 20 GW uses CCGT. The remaining 35 GW capacity is based on conventional steam turbines. Of the latter, 12 GW is dual fuel turbines which use both gas and oil as fuel input (IEA, 2003a).

The Japanese Central Research Institute of the Electric Power Industry (CRIEPI) mentions the followings reason for the share of conventional steam turbines in gas-fired power plants in Japan. Japanese general electric utilities started to implement gas-fired power plants in response to the oil crises of the 1970s. In those times gas turbines were not implemented yet on a large scale. As a result, utilities implemented conventional steam turbines. In the 1990s however, utilities implemented combined cycle power plants. Furthermore, utilities will implement more advanced combined cycle (MACC) with 59% (LHV) thermal efficiency, among the world's highest. The first MACC is expected to be online by July 2007.

Oil-fired power generation in Japan decreases from 208 TWh in 1990 to 91 TWh in 2003. The energy efficiency increases in this period from 42% to 45%.

4.1.7. Nordic countries

Total fossil-fired power generation in the Nordic countries is 80 TWh in 2003. Sweden and Norway both have limited fossil power capacity, and generate together only 7 TWh in 2003.

Coal-fired power generation in Finland, Denmark, Sweden and Norway was respectively, 26, 25, 4 and 0.1 TWh in 2003. The energy efficiency for coal-fired power generation of Nordic countries ranges from 40% to 42% in the period 1990–2003.

Gas-fired power generation is only significant in Denmark and Finland, which produce respectively, 8 and 12 TWh in 2003. Norway has no gas-fired power generation and Sweden generates only 0.4 TWh in 2003. The energy efficiency of gas-fired power generation is 46% in 2003 for the Nordic countries. Oil-fired power generation is very small, only 2 TWh in Denmark and 2 TWh in Sweden in 2003.

4.1.8. South Korea

Total fossil-fired power generation in South Korea is 182 TWh in 2003, of which 120 TWh is generated by coal, 40 TWh by gas and 22 TWh by oil.

The energy-efficiency for coal-fired power generation increases strongly from 26% in 1990 to 38% in 2003. Coal-fired power generation increases 10-fold in this period from 12 to 120 TWh.

The energy efficiency of gas-fired power generation increases from 41% to 51% in the period 1990–2003. Gas-fired power generation increases in this period from 10 to 40 TWh.

The energy efficiency of oil-fired power generation increases from 38% in 1990 to 44% in 2003. Oil-fired power generation increases from 19 in 1990 to 42 TWh in 1995. After that oil-fired power generation decreases to 22 TWh in 2003.

4.1.9. United Kingdom and Ireland

Total fossil-fired power generation in the United Kingdom and Ireland is 287 TWh in 2003, of which 142 TWh is generated from coal, 140 TWh from gas and 5 TWh from oil.

Due to the liberalisation of the electricity market in the early 1990s, several less efficient coal-fired power plants were closed in the UK, leading to a higher average efficiency of coal-fired power plants. In the following years (1996–1997), lower production of coal-based electricity was achieved by reducing the load factor of coal-fired power plants, resulting in a decrease of the average efficiency of coal-fired power plants. The energy-efficiency for coal-fired power plants in UK and Ireland is 38% in 2003.

As gas prices decreased, gas-fired power generation capacity increased significantly from 1992 onwards. The large addition of new capacity has resulted in a strong increase of the average efficiency of gas-fired power plants, from 40% in 1990 to 51% in 2003. Gas-fired power generation increased from 4 TWh in 1990 to 140 TWh in 2003.

Oil-fired power generation is very low, only 5 TWh in 2003.

4.1.10. United States

The United States is the largest fossil-fired power generator of the included countries and generates 2764 TWh in 2003, of which 75% is generated by coal.

The energy efficiency of coal-fired power generation remains fairly constant in the period 1990–2003, and is around 36%.

The energy efficiency of gas-fired power generation increases from 37% in 1990 to 42% in 2003. Electricity generation by gas-fired power plants increases strongly in this period from 283 to 627 TWh.

Oil-fired power generation is 121 TWh in 2003. The energy efficiency of oil-fired power generation is 36%.

4.2. Benchmark based on weighted-average efficiency

Table 1 shows the weighted average efficiencies for all countries and regions considered in this study.

Figs. 11, 12 and 13 show the deviation of the energy-efficiencies for respectively coal-, gas- and oil-fired power production from the yearly weighted average efficiency, in terms of percentage.

Note that a decrease of the benchmark indicator for a country might mean that the efficiency of the country has decreased or that the weighted average efficiency has increased.

Fig. 14 shows the benchmark indicator for the energy efficiency of fossil-fired power production.

5. Discussion of uncertainties

Uncertainties in the analysis arise in the first place from the input data regarding power generation, heat output and fuel input. This uncertainty is reduced by checking IEA statistics with national statistics. Still problems can

Table 1
Weighted average efficiencies of all countries and regions considered (%)

Weighted average efficiency	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Coal	34.7	34.9	34.8	34.8	34.9	34.6	34.6	34.3	34.3	34.8	35.0	34.9	34.9	35.2
Gas	38.0	38.4	38.5	39.0	39.7	40.5	41.0	41.5	41.9	42.6	42.3	43.1	43.8	44.6
Oil	38.4	38.5	38.9	38.4	39.1	38.6	39.0	38.5	37.8	38.1	38.5	37.9	38.4	38.3

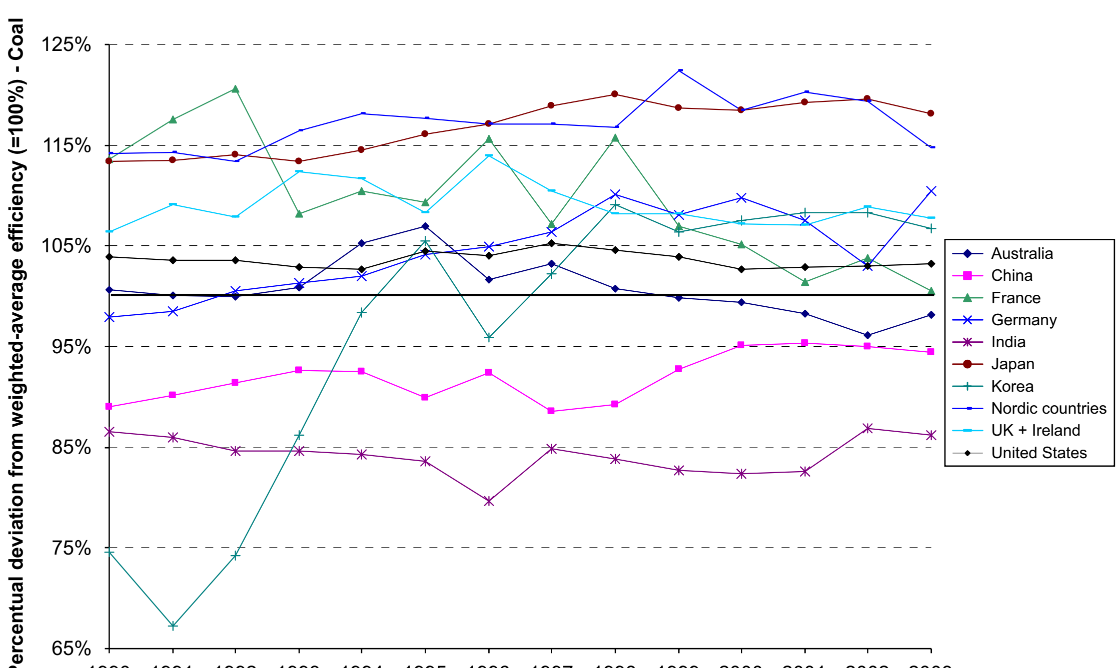

Fig. 11. Coal-fired efficiency relative to weighted average efficiency.

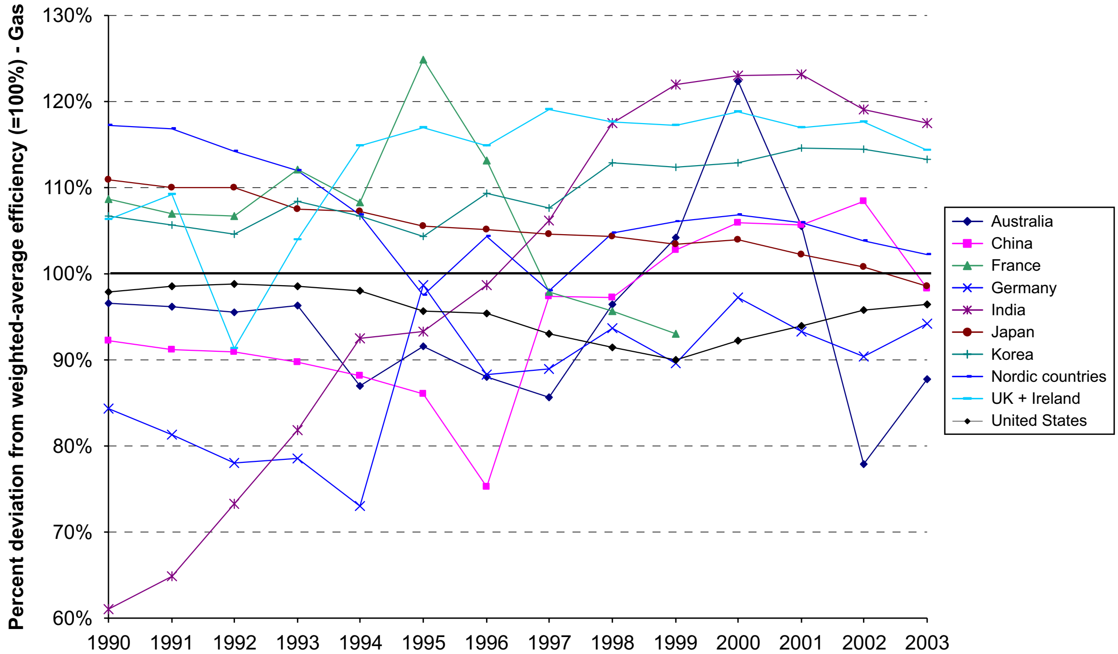

Fig. 12. Gas-fired efficiency relative to weighted average efficiency.

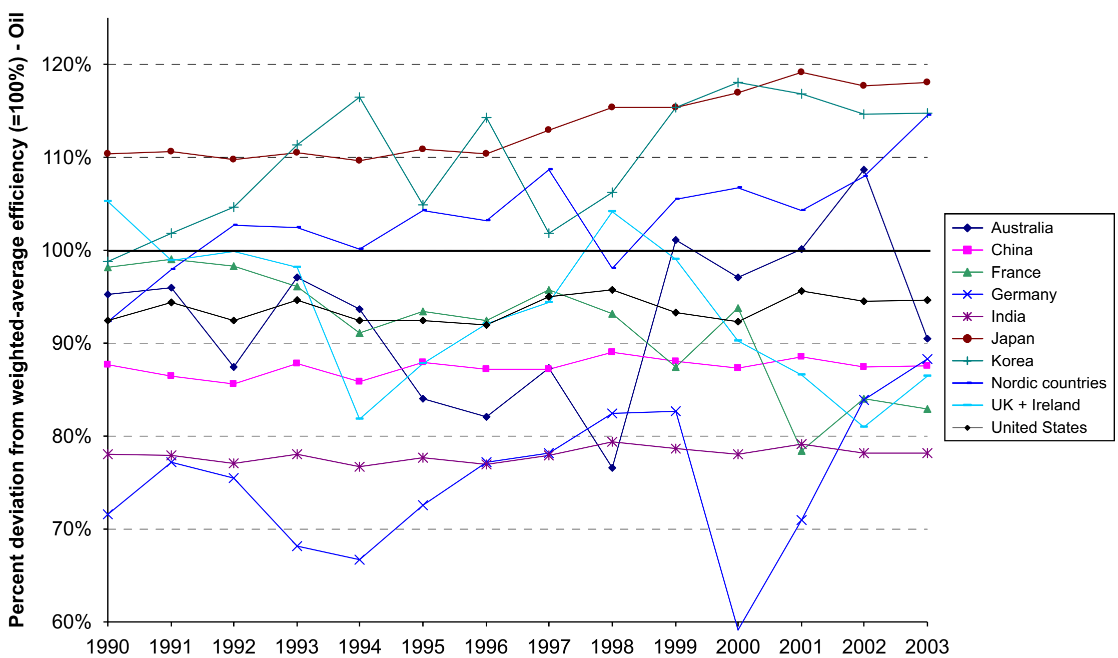

Fig. 13. Oil-fired efficiency relative to weighted average efficiency.

occur both in national and IEA statistics, resulting e.g. from estimates made by bureaus of statistic to calculate e.g. fuel input from power plants. In some cases fuel inputs are back calculated from assumed energy efficiencies. For follow-up research checks can be made with assistance of national experts to determine structural errors and inconsistencies in statistics.

A second source of uncertainty is the assumed energy efficiency loss resulting from heat generation. In this study, a factor of 0.175 is used. This may be different when heat is delivered at high temperatures (e.g. to industrial processes). We estimate that the effect on the average efficiency is not more than an increase of 0.5 percent-point.

A third source of uncertainty arises from structural factors that are not taken into account in the analysis. For instance, a higher ambient temperature leads to a slightly lower efficiency (0.1–0.2%/°C). Surface water cooling leads to slightly higher efficiencies than the use of cooling towers. The effect of cooling method on efficiency may be up to 1–2%.

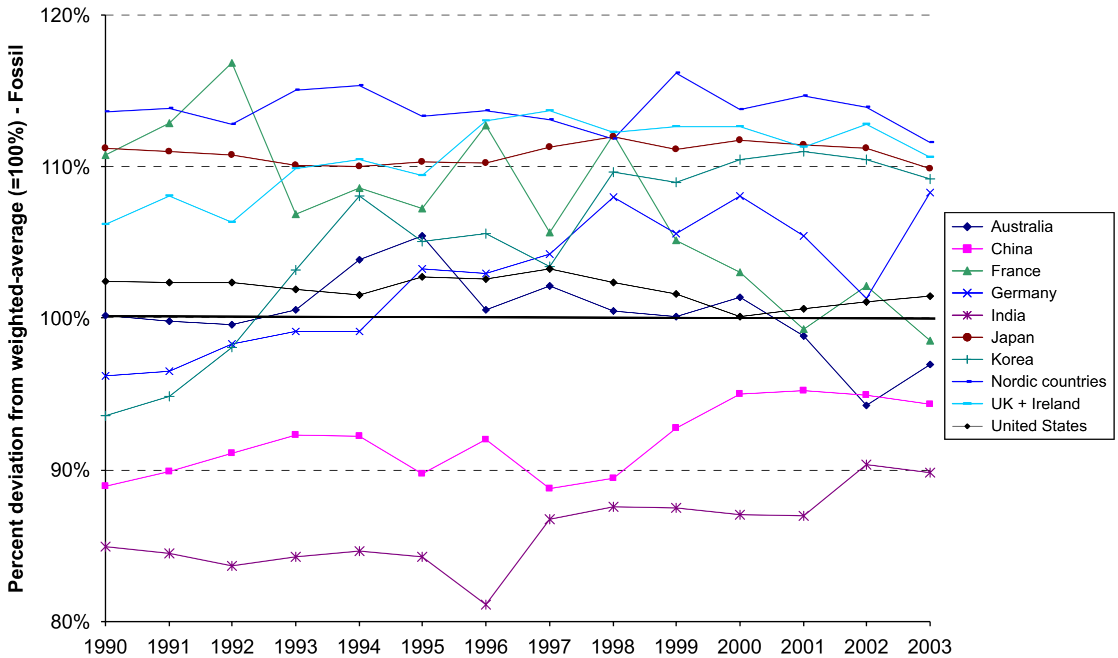

Fig. 14. Benchmark for energy-efficiency of fossil-fired power production (based on weighted average efficiencies).

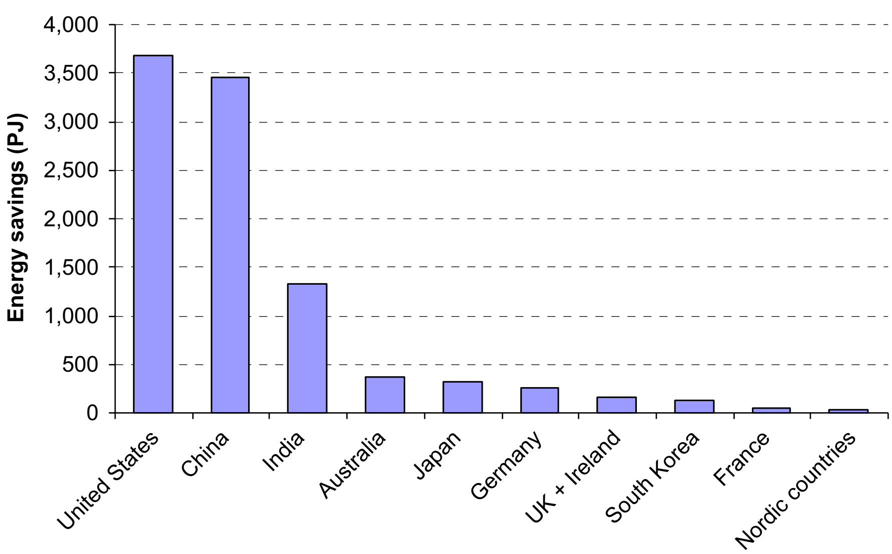

Fig. 15. Energy savings potential with highest efficiencies included countries.

6. Conclusion

The energy efficiency for fossil-fired power generation of the included companies shows a spread of 10% below to 12% above average efficiency. The results from the benchmark based on weighted average efficiencies shows that, the Nordic countries, United Kingdom and Ireland, and Japan, perform best in terms of fossil-fired generating efficiency and are respectively, 12%, 11% and 10% above average in 2003. South Korea and Germany are 9% and 8% above average efficiency in 2003 and the United States and France are 1% above and 1% below average, respectively. Australia, China and India perform 3%, 6% and 10% below average in 2003.

Figs. 15 and 16 show the energy savings potential and corresponding CO_2 emission reduction potential if all countries produce electricity at the highest efficiencies observed for the included countries (42% for coal, 52% for gas and 45% for oil-fired power generation). These graphs show that there is a large potential for CO_2 emission reduction in the power sector by energy efficiency improvement; in total 860 Mtonne CO_2 for the included countries. These countries generate 65% of worldwide fossil power generation. The potential for emission

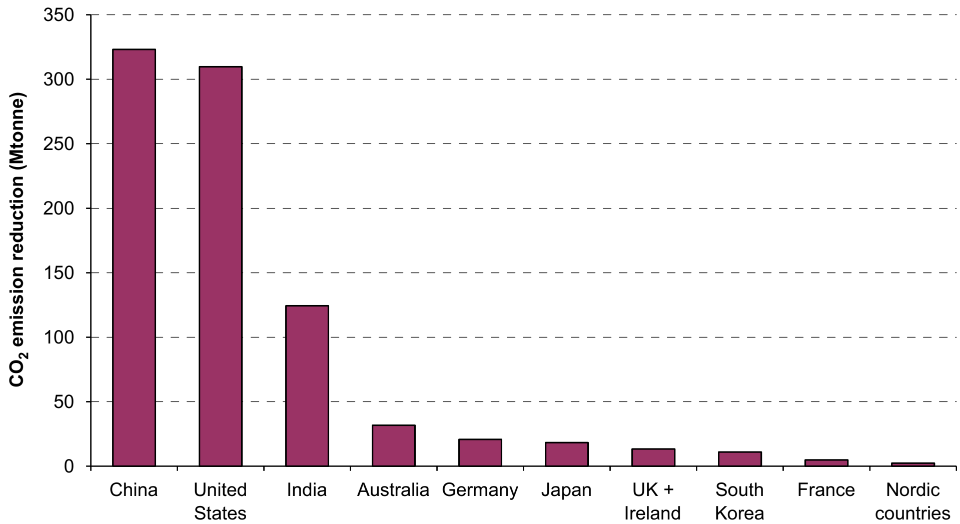

Fig. 16. CO_2 savings potential with highest efficiencies included countries.

reduction is higher when looking at best practise efficiencies for new power plant that are 47% for conventional coal-fired power plants (ultra-supercritical units) and 60% for natural gas-fired combined cycle plants (Hendriks et al, 2004). When looking at these best practise efficiencies the emission reduction potential for these countries is in total 1400 Mtonne CO_2.

Acknowledgements

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The views expressed in this paper do not necessarily reflect those of CRIEPI.

Appendix

Below, energy efficiencies based on IEA Energy Balances 2005 are compared to energy efficiencies calculated by available national statistics. We only mention differences between statistics if they are larger than 1%.

Australia

For Australia, energy statistics are available from the Australian Bureau of Agriculture and Resource Economics (ABARE, 2006).[3] These statistics give details about the input and gross output for total fossil-fired power generation by source for the year 2003–2004.

[3]Conversion factors used for converting from gross calorific value (GCV) to net calorific value (NCV) are 0.9 for natural gas, 0.93 for oil and 0.97 for coal.

The efficiency for coal- and gas-fired power generation in 2003 by IEA (2005a) is found to be close to the efficiency from ABARE (2006) for 2003–2004. For oil-fired power generation, the efficiency was found to be different, 34.7% by IEA and 36.1% by ABARE. Oil-fired power generation is however very small; only 0.4% of total public power generation. We will use IEA data for the energy efficiency of oil-fired power generation.

China

For China, the energy efficiency of fossil-fired power generation is checked by the China Energy Databook (LBNL, 2004) for the period 1990–2002.

For the years 1997–2002, the energy efficiency is found to be the same as the energy efficiency calculated by IEA (2005a). When looking in detail at the statistics from LBNL, it is found that the data for fossil-fired electricity generation and fuel input is different for the period 1990–1996. IEA reports ~3 percent point higher fossil-fired electricity generation than LBNL (2004). For instance for 1996, the efficiency for fossil power generation based on IEA (2005a), is 32% while the efficiency based on LBNL (2004) is 29%. For 2002, the energy efficiency is 33% according to both sources.

We decide to use IEA data for the whole period, because no data is available from LBNL (2004) on the electricity generation by fuel source. Only the total fossil-fired power generation is available.

France

Fossil-fired power generating capacity is very small in France. No detailed energy statistics could be found to calculate energy efficiency. Data on electricity production from fossil-fuel sources is available from INSEE (2005), but this data includes electricity generation from

Table 2
Energy efficiency fossil-fired power generation (%)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
IEA (2005b)	33.6	34.0	34.5	34.6	34.7	36.3	35.2	35.4	37.9	37.6	38.6	37.8	37.0	39.3
Energiebilanz 2004[a]	35.8	36.2	36.5	36.7	36.7	37.1	37.8	38.0	38.6	38.4	38.9	39.0	38.8	39.6

[a]The efficiency calculated by Energiebilanz is not corrected for heat generation because in these statistics fuel consumption for heat generation is not included in the fuel input data.

auto-producers. Total thermal power generation in 2002 is 50.3 TWh by INSEE in comparison to 27.6 TWh for public power generation given by IEA.

A calculation based on European Commission (2003) gives an energy efficiency for fossil-fired power generation in France of 37.9% for 2000 in comparison to 37.1% by IEA (2005a). No other detailed energy statistics were available for France, for this study, to look further into this.

Germany

For Germany we looked at the Energiebilanz 2005 from Arbeitsgemeinschaft Energiebilanzen (2005). Table 2 shows the results for the energy efficiency for fossil-fired power generation calculated by IEA (2005a) and by the Energiebilanz 2005. The data from Arbeitsgemeinschaft Energiebilanzen refer to total electricity generation, including electricity generation by auto-producers. The IEA data refer to public power generation. Public power generation is 93% of total power generation in Germany in 2003 (IEA, 2005b).

The difference in energy efficiency may be caused by the fact that the fuel input data in Energiebilanz only includes fuel consumption for electricity generation and not for heat generation. Total fuel consumption of public CHP plants in Germany is 15% of total fuel consumption by fossil-fired public power plants in 2003 (IEA, 2005b). This could explain the fact that the energy efficiency found in the Energiebilanz is generally higher than the IEA values. Since no other detailed energy statistics are available for Germany for this study, we will use IEA (2005a) for Germany.

India

For India, energy statistics are available from the Ministry of Statistics and Programme Implementation (MOSPI, 2006). After comparing these statistics to IEA statistics we noticed that thermal power generation in both sources is the same. The oil input in thermal power plants was also found to be the same.[4] For coal input a difference was found of 10–12% higher coal input in IEA statistics for the period 1990–2003. We found that the reason for this could be different conversion factors to convert from tonne coal to energy. IEA uses e.g. a conversion factor of 18 GJ/tonne coal for India for 2003, while MOSPI uses a conversion factor of 16.6 GJ/tonne coal based on GCV for 2003 (16.1 GJ/tonne based on NCV, with 0.97 conversion from GCV to NCV). This explains the difference in higher coal input in IEA statistics. TERI (2004) gives even lower values for coal input for power generation than MOSPI (2006); 4.3 vs. 4.5 PJ in 2001. IEA gives 5.0 PJ for 2001. In this analysis we will use the fuel input data for coal (corrected to NCV) from MOSPI (2006) to calculate the energy efficiency for coal-fired power generation.

Table 3 shows the energy efficiency of coal-fired power generation based on IEA and the energy-efficiency based on fuel input for coal from MOSPI (2006).

For oil- and gas-fired power generation we just use the values from IEA statistics. Natural gas consumption for power generation is not available in MOSPI (2006).

Japan

For Japan, the efficiency of fossil-fired power generation is calculated for the period 1990–2003 by METI (2004).[5] Some slight differences are present between the calculations based on IEA (2005a) and METI (2004), but these differences are below 1%.

When comparing energy efficiency by fuel source it was found that there are differences in power generation by fuel source between the two data sources coal-, gas- and oil-fired power generation by METI (2004) in 2003 is respectively, 212, 273 and 84 TWh. IEA (2005a) gives 243, 244 and 91 TWh, respectively for 2003.

A reason for this difference may be a difference in the methodology for distributing power generation in case of dual fuel power generation. METI (2004) provides data on electricity generation by plant. In IEA data, electricity generation is split up by fuel source. This can lead to different results if e.g. a gas-fired power plant or unit

[4]Calculation is based on 42.7 MJ/kg for diesel oil and 41 MJ/kg for heavy fuel oil.

[5]Statistics are based on data for public power generation with the exception of specified-scale electricity suppliers; named Power Producers and Suppliers (PPS). These PPS generate less than 1% of total public power generation. Data is converted from GCV to NCV by conversion factors from RIETI (2005).

Table 3
Energy efficiency of coal-fired power generation (%)

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
IEA (2005a)	26.6	26.6	26.3	25.3	25.6	25.6	25.6	25.7	25.8	26.8	26.8
Fuel input coal from MOSPI (2006)	29.4	29.4	29.0	27.6	29.1	28.8	28.8	28.8	28.8	30.3	30.4

consumes oil products or coal products (e.g. coke oven gas or blast furnace gas) as well as natural gas. The electricity generation can then be divided into coal-, gas- and oil-fired power generation or can be entirely included in natural gas-fired power generation.

A comparison of fuel input data from METI and IEA shows that for natural gas the fuel input data is nearly the same. For coal-fired power generation IEA reports a slightly higher value for fuel input (1–2%). This is compensated by a lower fuel input for oil-fired power generation (~2%).

The difference in power generation leads to a difference in energy efficiency by fuel source. The energy efficiency of coal-, gas- and oil-fired power generation calculated by METI (2004) is around 40–41%, 46–47% and 39%, respectively, based on a plant level. The efficiencies based on IEA (2004) are respectively, 41.9%, 44.2% and 45.3% for the year 2002.

Because overall fossil-fired power generation efficiency calculated by METI (2004) and IEA (2005a) is similar for all years, no changes are made to the data for Japan.

In this way the data are most comparable to the data for the other countries, because they are based on the same methodology.

Nordic countries

For the Nordic countries we compared IEA statistics to national statistics for Denmark and Finland since these countries together generate 87% of the total fossil-fired power generation of the Nordic countries in 2002. For Sweden and Norway we will use IEA statistics.

For Denmark, energy statistics are available from the Danish Energy Authority (2005). These statistics give details about total fossil-fired power generation for the period 1990–2004. The efficiency for fossil-fired power plants is for most years equal to the efficiency based on IEA (2005a). Some slight differences can be caused by the fact that biomass co-firing is included in the Danish Energy Authority's data. We decided therefore to use IEA data for Denmark for the whole period.

For Finland, IEA statistics are compared to Energy Statistics 2003 (Statistics Finland, 2004). It is difficult to compare these two statistics because in Finnish statistics, fuel consumption for combined heat and power (CHP) plants is partly included in the category "fuel consumption for electricity generation from CHP plants" and partly in the category "fuel consumption for district heat and heat from combined heat and power plants." No further split up is available for the last category. Additionally heat generation in CHP plants is not available by fuel source and includes heat generated by biomass. Biomass consists for 13% of the fuel consumption for public CHP plants in 2002 (IEA, 2004). Lastly, Finnish energy statistics include autoproducers.

Especially the first point is a problem, since 35% of fossil-fired power generation in Finland in 2003 is generated in CHP plants (IEA, 2005b). In order to compare energy efficiencies, we back-calculated the energy consumption for heat generation by CHP plants[6] and added this to the energy input for electricity generation. The results are shown in Table 4.

As can be seen in Table 4, the differences in energy efficiency based on these assumptions are not so large, except for the period 1995–1999.

Because of the mentioned differences in definitions in IEA statistics and Statistics Finland (2004), and the difficulty comparing the two, no changes are made for Finland.

South Korea

For South Korea, energy statistics are available from the Korea National Statistical Office (KOSIS, 2006) and from Korea Electric Power Corporation (KEPCO, 2006).[7]

Table 5 shows energy efficiency by fossil-fired power generation, calculated by both sources.

We will use the energy-efficiencies for fossil-fired power generation from KOSIS because these values are more consistent than the IEA values and because the number are more similar to the values found from KEPCO.

Table 6 shows the energy efficiency of power generation by source, calculated by IEA and KEPCO. KOSIS does not provide data on power generation by fuel source. The table shows the energy-efficiency values that are used in this study. The efficiencies are mostly based on the data from KEPCO, because these values are more consistent than the IEA values.

[6]This is based on 90% efficiency for alternative heat generation. The heat output from CHP plants is corrected for the input from biomass by subtracting the share of biomass input from total heat generation, in terms of percentage, for all years (IEA, 2005a).

[7]Conversion factors used for converting from physical units to NCV are 26.6 MJ/tonne anthracite, 25.7 MJ/tonne bituminous coal, 41 MJ/kl heavy oil, 34.2 MJ/kl diesel and 49.5 MJ/tonne LNG (based on NCVs for South Korea from IEA and IPCC default values). Heat generation is not available and is taken from IEA (2005a) for natural gas and for total fossil-fired power generation.

Table 4
Energy efficiency of fossil-fired power generation in Finland (%)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
IEA (2005b)	41.6	41.2	41.7	41.2	41.6	38.5	38.6	37.2	40.0	43.2	42.7	42.9	42.3	40.7
Statistics Finland (2004)	41.3	41.0	42.1	41.7	41.7	42.0	41.8	42.3	43.5	44.1	43.1	42.0	42.2	41.3

Table 5
Energy efficiency of fossil-fired power generation (%)

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
IEA	37.8	40.3	39.2	39.2	38.0	40.1	38.7	37.8	37.8	42.8	39.7
KOSIS	36.7	38.2	38.3	38.6	38.9	39.3	39.2	39.4	39.9	40.3	40.1
KEPCO	—	—	—	—	36.0	40.1	40.2	40.1	40.1	—	—

Table 6
Energy efficiency of power generation by source (%)

	Source	1997	1998	1999	2000	2001	2002	2003
Coal	IEA	35.1	37.3	36.5	35.7	37.0	42.4	37.6
	KEPCO	31.9	37.4	37.0	37.6	37.8		
	Used values	35.1	37.4	37.0	37.6	37.8	37.8[a]	37.6
Gas	IEA	45.2	49.3	47.1	44.0	41.7	50.1	50.6
	KEPCO	44.7	47.3	47.9	47.7	49.4		
	Used values	44.7	47.3	47.9	47.7	49.4	50.1	50.6
Oil	IEA	37.5	40.1	35.6	39.2	36.3	34.8	36.4
	KEPCO	39.2	46.3	49.4	45.4	44.3		
	Used values	39.2	40.1	44.0[a]	45.4	44.3	44.0[a]	44.0[a]

[a]Assumption.

United Kingdom and Ireland

For the United Kingdom and Ireland, we only compared IEA statistics to national statistics for the United Kingdom, because they generate 92% of the total fossil-fired power generation of the United Kingdom and Ireland in 2003. For Ireland we use IEA statistics.

Energy statistics for the United Kingdom from DTI (2006) give data for the years 1996–2004.[8]

The energy efficiency for gas-fired power generation, calculated by DTI (2006) and IEA (2005a), is found to be the same.

For coal-fired power generation the energy efficiency is different for the year 2000; 37.4% by DTI in comparison to 40.3% by IEA. For 2001, 2002 and 2003 the deviation is less than 1%. We use 37.4% for 2000 because this value is more in line with the energy efficiencies for the other years (37.7% in 1999 and 37.3% in 2001).

[8]Conversion factors used for converting from gross calorific value (GCV) to net calorific value (NCV) are 0.9 for natural gas, 0.93 for oil and 0.97 for coal. The gross calorific values are taken from DTI Annex B Calorific Values and Conversion Factors. http://www.dti.gov.uk/energy/inform/energy_prices/annex_b_mar04.shtmland

Table 7
Energy efficiency of coal-fired power generation (%)[a]

	1990	1991	1992–1999	2000	2001	2002	2003
IEA (2005a)	37.2	37.3	36	36.5	35.0	35.9	36.4
EIA (2005)	36.1	36.1	36	35.9	35.9	36.1	36.2
Ratio: IEA/EIA	103	103	100	101	97	99	100

[a]Data from IEA (2005b) is based on gross calorific value. This is converted to net calorific value by a factor of 0.97 for coal, 0.9 for natural gas and 0.93 for oil.

United States

For the United States, energy efficiencies are calculated from the Annual Energy Review 2004 (EIA, 2005).

A number of differences were found between EIA and IEA data. Some of these differences may be caused by the fact that EIA reports electricity data in terms of net electricity generation instead of gross electricity generation. The data from EIA are converted to gross electricity generation by a factor of 1.06 for coal, 1.03 for gas and 1.04 for oil.[9]

Table 7 shows energy efficiency by coal-fired power generation, calculated by both sources.

The energy efficiency for coal-fired power generation differs for the years 1990, 1991, 2000 and 2001. The energy efficiency for these years, based on EIA, is more in line with the energy efficiency for the years 1992–1999 and 2002. Therefore we replace IEA data by EIA data for these years.

Table 8 shows energy efficiency by gas-fired power generation, calculated by both sources.

[9]Gross electricity generation refers to the electric output of the electrical generator. Net electricity output refers to the electric output minus the electrical power utilised in the plant by auxiliary equipment such as pumps, motors and pollution control devices. These auxiliaries typically utilize 3–6% of a plant's gross output (FirstEnergy Corporation, 1999). Auxiliary consumption is in general higher for coal-fired power plants than for gas-fired power plants. In this study, we use 6% for coal-fired power generation, 3% for gas-fired power generation and 4% for oil-fired power generation. These values result in figures that are most consistent with the gross electricity generation figures from IEA (2005a).

Table 8
Energy efficiency of gas-fired power generation (%)

	1992–1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
IEA (2005a)	38	39	38.2	38.3	38.0	37.5	37.8	39.6	40.5	41.9	43.1
EIA (2005)			38.7	39.1	38.6	38.3	38.4	39.0	40.5	42.1	45.4
Ratio: IEA/EIA	100	100	99	98	98	98	98	102	100	99	95

Table 9
Energy efficiency of oil-fired power generation (%)

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
IEA	38.2	37.9	37.3	36.9	38.0	37.9	37.0	52.4	56.3	40.7	42.4
EIA	36.3	36.1	35.7	35.9	36.6	36.1	35.6	35.5	36.2	36.3	36.6
Ratio: IEA/EIA	105	105	104	103	104	105	104	148	155	112	116

For gas-fired power generation the difference in energy efficiency between the two sources is less than 1% for the years before 1995. From the period 1995–2000 EIA's energy efficiency is ~2% higher. We will take EIA data for this period, because this data shows fewer fluctuations. For 2003 we take IEA data.

Table 9 shows energy efficiency by oil-fired power generation, calculated by both sources.

As can be seen in Table 9, there are large differences in the efficiency of oil-fired power generation. We will replace IEA data with EIA data for oil-fired power generation because the EIA dataset seems more reliable, especially for the years 2000–2002, with fewer fluctuations.

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