

# How did the efficiency of coal-fired power stations evolve, and what can be expected in the future? <sup>1</sup>

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## Summary

Generation of electricity using coal started at the end of the 19<sup>th</sup> century. The first power stations had an efficiency of around 1%, and needed 12.3 kg of coal for the generation of 1 kWh. This meant 37 kg  $CO_2$  emissions per kWh.

With increasing experience, in combination with research and development, these low efficiency levels improved rapidly. Increased technical experience with coal processing and combustion technology enabled a steady increase in the steam parameters 'pressure' and 'temperature', resulting in higher efficiency. In the years 1910, efficiency had already increased to 5%, reaching 20% by 1920. In the fifty's, power plants achieved 30% efficiency, but the average efficiency of all operating power plants was still a modest 17%. In the next stage, the use of cooling towers for the removal of heat that could no longer be converted to electricity became a requirement, in addition to the removal of  $SO_x$  and  $NO_x$  from exhaust gasses, resulting in a reduction of efficiency, since these facilities use energy. However, continuous development resulted around the mid 80's in an average efficiency of 38% for all power stations, and best values of 43%. In the second half of the nineties, a Danish power plant set a world record at 47%.

Power stations based on brown coal are a few % less efficient than stations using hard coal, because of the different nature of the fuel. Nevertheless, RWE's brown coal optimised power station 'BoA' that started operation in 2002, reached 45.3% efficiency, the highest value ever achieved by a brown coal power station.

The average efficiency of all coal power stations in the world is around 31%. Hence, there is an enormous potential to reduce coal consumption and  $CO_2$  emissions.

For the next 20 years, the EU-15 needs an additional 100 000 MW new capacity and replacement of 200 000 MW existing capacity. Hence, a significant development in coal generation technology is taking place. In the next 10 years, efficiencies up to 55% can be

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expected. This means 223 g coal equivalent (CE) per kWh<sup>2</sup>.

Current and future efficiencies for coal-fired power stations, using comparable terms of reference, are in the upper ranges of all electricity generation technologies.

## 1 Introduction

With a share of 23% in 2002, coal (brown coal and hard coal) is at present one of the major energy sources for mankind and is expected to remain important for the foreseeable future. In 2002, the world used about 3.4 billion tCE<sup>3</sup>. The major part (2.8 billion tCE) was used for generating 7 000 billion kWh of electricity. The complete combustion of a tCE generates 8140 kWh heat.

This energy is combustion energy, or thermal energy ( $kWh_{th}$ ). It contains energy that can be converted in work up to a certain extent ('exergy'). The remaining part cannot physically be converted into work, and is known as 'anergy'. Combustion heat is transferred with over 90% efficiency to water in the boiler of a power station. This creates steam. The higher the pressure and temperature of steam, the higher its exergy, i.e. the part of the energy in the steam that is able to perform work. The pressurised steam is used for rotating a steam turbine. Hence, physical work, stored in steam, is extracted in a turbine. The turbine is connected on the same axis to a generator, that converts this work into electricity ( $kWh_{el}$ ). Electricity can be used almost entirely to perform work (with motors, 98% can be converted into physical work). In contrast to all other end-use energy carriers, electricity is almost pure physical work (exergy). Because of this reason, the electrical kWh is sometimes called work-kWh, in order to distinguish it clearly from thermal kWh<sup>4</sup>.

The waste heat after above extraction process, through the removal of the work energy in the steam, has a remaining temperature of 30 degrees. The steam after expansion has no more pressure, and is so 'weak' that its remaining energy can no longer be converted into electricity. It is 'anergy', that usually is dissipated in the atmosphere through cooling towers. This has no environmental impact, since these waste energies can be ignored compared to the total energy in the atmosphere.

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<sup>2</sup> 1 tCE = 1 tonne coal equivalent = 7 Gcal = 23.91 GJ (GigaJoules) = 8140 kWh<sub>th</sub> (kWh thermal). It is the energy contained in a tonne of good quality coal, 3 tonne brown coal, or 0.7 tonne mineral oil.

<sup>3</sup> In this paper, billion is used as 1 000 million (Giga, 10<sup>9</sup>) <sup>4</sup> An essential difference that is too often overlooked in public debates, leading to misunderstandings and misjudgments. The incorrect use of the term 'exergy' for heat in buildings further adds to the confusion. This is not its definition.

The efficiency of conversion is governed by the laws of physics, and depends on the ratios of steam pressure and temperature at the input and output of the turbine. Low temperatures at the output, through cooling in the condenser, lead to higher efficiencies. This effect is further enlarged through direct cooling, for example using sea-water.

## 2 The past development of efficiency

In the 19<sup>th</sup> century, coal was used primarily for heat in homes and increasingly in industry to support and control chemical processes. Generation of power started at the end of the 19<sup>th</sup> century. Mainly steam piston engines were used at the time. These operated at about 1% efficiency<sup>5</sup>. This means that 81.4 electrical kWh could be generated from 1 tCE. Or production of an electrical kWh ( $kWh_{el}$ ) required 12.3 kg CE. Combustion of 1 kg coal results in approximately 3 kg  $CO_2$ . Hence, a  $kWh_{el}$  resulted in 37 kg  $CO_2$  emissions. This gas is not poisonous. Without  $CO_2$ , life on earth as we know it would be impossible. But in the view of many experts, too much  $CO_2$  endangers the world's climate, through global warming.



Figure 1: Steam driven electricity generators in Budapest (1895). Designed and produced by Ganz company (courtesy Elektrotechnika – Hungary)

Early development of power generation technologies naturally focussed on improvement of their economic feasibility. A major instrument was efficiency improvement. Improved efficiency reduced the amount of coal used, and the cost per kWh. Equally important, it reduces emissions per kWh of  $CO_2$ ,  $SO_x$  and  $NO_x$ . Therefore, an increased efficiency serves both economic and environmental objectives.

Through increasing experience, in combination with R&D, efficiency started to rise quickly and significantly in Germany. A multitude of new insights and technical developments allowed improvement of almost any component in the power station. Examples are continuous improvement of combustion technology and the endurance characteristics of materials - either new materials, or fur-

<sup>5</sup> Efficiency = produced amount of electricity divided by amount of energy consumed. For example, if 1 tCE produces 3100 kWh(el), then efficiency is  $3100 \text{ kWh}(\text{el}) / 8140 \text{ kWh}(\text{el}) = 0.381$ , or 38.1%.

ther developed existing materials<sup>6</sup>.

Only in this way was it possible to achieve an increase in steam parameters, and hence a higher exergy content (work kWh content) of the steam. In addition, intermediate heating<sup>7</sup> of the steam are significant milestones in the steady increase of efficiency. In addition, size of power plants increased, with corresponding larger combustion chambers, and longer combustion paths, allowing a more effective coal combustion. Water preheating, using waste heat, and steam from the turbine, in addition to reducing heat losses, for example through the walls of the boiler, further significantly increased efficiency. The most effective measure, though, remained a steady increase of steam parameters. Around 1910, 13 bar and  $275^{\circ}\text{C}$  had already been achieved, enabling 5% efficiency, and hence 5 times better use of coal. In the early twenties, steam parameters of 36 bar and  $450^{\circ}\text{C}$  (20% efficiency) became possible. Through further developments, new power plants in the fifties operated with 150–180 bar and  $450^{\circ}\text{C}$ , under 30% efficiency. Specific use of coal amounted to 728 gr CE per kWh. But the average efficiency of all power stations was still a moderate 17%. In the following decades, the efficiency of using coal further increased. The increase was slowed down by the need to use cooling towers and the addition of energy-using facilities on-site for desulphurisation and reduction of nitrogen oxide in the exhaust gasses (having a 2-4% impact on efficiency). In the middle of the eighties, best values of 43% were achieved nevertheless (260 bar,  $540^{\circ}\text{C}$ ). The average efficiency of all power stations was around 38% (323 gCE / kWh). In this way, the specific coal usage was reduced by a factor 38 over a period of 80 years. Since then, the average efficiency has further increased slightly, through closure of older power stations. A coal-fired power station constructed with the newest technology in Denmark near the coast that started operation in the second half of the nineties, achieved the world's best efficiency at the time of 47% through direct cooling with seawater.



Figure 2: Combined-cycle power plant in Malaysia  $2 \times 400\text{MW}$  (© Siemens)

<sup>6</sup> Baseload stations operate 8 000 hours/year, medium load stations between 2 000 and 4 000 hours. Extreme requirements need to be managed, e.g. against CO corrosion, anti-inflammability, pressure and temperature changes, . . . . Materials must sustain these requirements of aggressive/abrasive gasses and steam under high pressure for a duration of at least 100 000 hours (a year has 8 760 hours), in order to avoid repeated, unplanned, often long and expensive production stops, leading to high penalties because of not honouring the supply contract. Materials that must meet these '100 000 hour values', hence need to be tested for several years under operation conditions. <sup>7</sup> I.e. passing the steam, after expansion in the turbine, again through the boiler for a second cycle

Efficiency of brown coal power stations is a few percent points lower than their hard coal equivalents. This relates to the different properties of coal. The higher water content of brown coal requires more energy to dry it to 18% water content. Water has a high vaporisation energy, and its vaporisation during combustion uses a relatively high part of the exergy content in the combustion gasses, which can then no longer be transferred to steam to drive the turbine. The amount of water vapour in the combustion gasses of brown coal is hence larger than for hard coal. In addition, the mere fact that 1 tonne hard coal is equivalent to 3 tonnes brown coal, results in more exhaust gasses, and hence more energy loss through the chimney at the same temperature. The world's best brown coal-fired power station, with installed capacity over 1 000 MWe, nicknamed 'BoA'<sup>8</sup> that RWE started to operate in 2002, achieved nevertheless 45.3% net efficiency<sup>9</sup>. For subsequent new facilities, it is planned to evaporate the water content in brown coal using exergy-low waste heat in a special processing facility. If this can be successfully developed, it will further increase efficiency.

The average efficiency of coal-fired power stations in the world currently is a moderate 31%. Many regions in the work have therefore significant potential to increase efficiency, and reduce emissions.

### **3 Are further increases in efficiency possible?**

Germany needs to replace between 2010 and 2030 about 40 000 MW of capacity, due to ageing. The European Union of 15 has an additional need of 100 000 MW, and needs to replace 200 000 MW. In addition, Germany needs to replace its nuclear capacity of 21 000 MW (if these facilities are actually phased out). Wind turbines or photovoltaic facilities cannot provide such capacity in an economic or even ecological manner. In addition, one has to consider the intermittent nature of these power sources, which makes them inadequate for reliable power supply for households, commerce, industry or public transport. Except in special cases, they cannot be used on a large scale. Also hydrogen – an excellent fuel – is not an option, even in the medium term, because of the extremely low efficiency of its production and use chain. It occurs in nature only in its bound form (in water, but also natural gas, mineral oil and coal) and needs to be extracted, using a large amount of exergy, and hence high losses. Eurelectric<sup>10</sup> expects a significant increase in the share of natural gas. But prices for natural gas are relatively high, and generation costs are higher than for nuclear or coal-fired power plants. And prices for natural gas in several countries are subject to significant economic risks and strong price movements. As a result, an increased usage of coal-fired power is expected in Germany, among others.

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<sup>8</sup> Braunkohlekraftwerk mit optimisierter Anlagentechnik or Brown coal power station with optimised process <sup>9</sup> Net efficiency means after deduction of the power station's own power needs for auxiliary facilities, lighting, ... <sup>10</sup> Union of the Electricity Industry – www.eurelectric.org.

	$\mu(\%)$	gCE/kWh	$gCO_2/kWh$
China/Russia	23	534	1 600
World	31	396	1 188
Germany	38	323	969
Best available technology	55	223	669
Future	60 – 65	205 – 189	612 – 567

Table 1: Average efficiency, specific coal usage,  $CO_2$  emissions

VGB Powertech<sup>11</sup> has started in the EU a concentrated initiative – ‘E-max’ – to significantly increase power plant efficiency by the beginning of the next decade:

- In 1998, project ‘KOMET 650’ started<sup>12</sup>. The goal is an increase of steam parameters to a temperature of  $650^\circ C$  and a pressure of 280 bar. This would enable 47% efficiency. Tests in 14 individual projects have been successfully concluded. A reference power plant in Nordrhein-Westfalen is being planned.
- The project ‘Advanced  $700^\circ C$  Power Plant (AD 700)’, started by the Danish power industry, targets steam parameters of  $700^\circ C$  and 350 bar. The objective is 55% efficiency. The planning phase was completed in 2002. Testing has started with a partnership of 35 consultancies, manufacturers, power producers and R&D institutes. By 2005, the results from a demonstration power plant of 400 MW should be available.
- The COORETEC initiative ( $CO_2$  reduction technologies) of the German Economics and Labour Ministry aims for an ‘emission-free’ coal-fired power station<sup>13</sup>. Regarding  $CO_2$ , sequestration techniques are being investigated, but it is at present not clear at all how secure storage of the large masses (at least 3 times the mass of coal used) can be realised. Feasibility is being investigated by industry in partnership with 2 institutes. In the USA, similar investigations are being done.

Other options are variations of a combination of coal gasification with combined-cycle steam & gas turbines to use the advantages of the gas turbine (STAG: steam and gas power plant)<sup>14</sup>.

Large-scale trials for such plant have been started in Germany in 1968, and currently take place internationally. So far, the combination of both techniques – coal gasification

<sup>11</sup> International Technical Association of power producers – [www.vgb-power.de](http://www.vgb-power.de)

<sup>12</sup> Kraftwerks-Optionen: Material- und Messtechnik-Entwicklungen und ihr Test unter Betriebsbedingungen. <sup>13</sup> I.e. ‘reduced emissions’, since an absolutely ‘emission-free’ power station is impossible. <sup>14</sup> Combined-cycle steam and gas power plants, based on natural gas, make better use of primary energy through the complementarity of steam and gas parameters. It helps that natural gas is already a pure fuel, so that the STAG power plant’s own exergy use is significantly reduced. In addition, gas is delivered to the station under pressure, with additional exergy content, which does not consume the thermal energy of the gas.

(with steam generation) and coal combustion – has not been successful. Both plant concepts are structurally different in their technology, for example regarding their partial load characteristics. In addition, coal gasification has an efficiency that is significantly below 100%. Hence, the energy input into a steam and gas power plant is much less compared to a coal-fired power station. The efficiency reduction must be recovered by the subsequent combined-cycle process. This requires additional technical measures. It has been demonstrated that the reliable and relatively simple steam process can achieve similar efficiencies. Despite the difficulties, these advanced new concepts remain interesting enough to justify continued developments.

Another trial is the direct combination with coal combustion under pressure. Coal is combusted under high pressure and temperature, and the hot flue gasses, after removal of dust, particles and chemicals that could damage the turbine, are being used in a gas turbine and subsequent steam power plant. Technical problems are a.o. the separation of solid and gas mineral components in the flue gasses under high pressure and temperature, as well as the contamination and erosion of the turbine by the fraction of ashes and slags that remains. Experiments are in their early stage. The very extensive development could lead to near 60% efficiency, a level already achievable today with STAG plants using natural gas.

## 4 Conclusion

It seems feasible to have 55% efficiency available for the necessary replacement and addition of coal-fired power capacity.

Current and future efficiency of coal-fired power stations, under similar boundary conditions, compare favourably with the upper range of any other power generation technology.

## Note

Often, the question is asked why the 'other 45%' cannot be converted into electricity. This relates to the laws of physics: the absolute maximum efficiency is the so-called 'Carnot efficiency'. For a turbine operating with gasses of 600°, it is 67%. Then we need to take into account the exergy content of steam (around 94%). Also combustion has an efficiency less than 100% (around 95%). The transfer of combustion heat to steam in the boiler is for example 96% efficient. Losses due to friction can be around 5% (efficiency 95%). The efficiency of a generator is about 98% on average . . .

To obtain the combined efficiency, one needs to multiply the efficiency of each process. Taking the above mentioned components, one obtains  $0.67 \times 0.94 \times 0.95 \times 0.96 \times 0.95 \times 0.98 = 0.535$  or 53.5%.

This does not yet take into account the efficiency of all components. The power station's own power use for motors to grind coal, pumps, ventilators, . . . further reduces efficiency. In practice, net efficiency will be around 40 and 45%. Continuous load changes, i.e. following the load, and start-up/shutdown procedures further lower efficiency<sup>a</sup>. The increasing variability of the load, through increased use of intermittent sources such as wind, will lead to increased swings in the load of the power station, reducing efficiency. This results in increased use of coal, and increased  $CO_2$  emissions.

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<sup>a</sup> Similar to a vehicle, using more fuel in city traffic due to the continuous speed changes. Continuous base load, as on a highway, significantly reduces fuel consumption.

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