International Energy Agency


# Emissions Reduction through Upgrade of Coal-Fired Power Plants

Learning from Chinese Experience

International Energy Agency

PARTNER COUNTRY SERIES

# Emissions Reduction through Upgrade of Coal-Fired Power Plants

## Learning from Chinese Experience

Keith BURNARD and Julie JIANG, IEA
Bo LI and Gilbert BRUNET, EDF
Franz BAUER, VGB PowerTech

## INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

**IEA member countries:**

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea (Republic of)
Luxembourg
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

The European Commission also participates in the work of the IEA.

International Energy Agency
1974•2014
Secure • Sustainable • Together



**International Energy Agency**
9 rue de la Fédération
75739 Paris Cedex 15, France

***www.iea.org***

# Table of contents

## List of figures



## List of tables



## List of boxes

# Acknowledgements

This publication was prepared by the International Energy Agency (IEA), under the leadership and guidance of Kenneth Fairfax, Deputy Executive Director, and Didier Houssin, Director of Sustainable Energy Policy and Technology. It is produced under the authority of the Executive Director of the IEA, Maria van der Hoeven.

The project was managed by Keith Burnard and Julie Jiang, who had overall responsibility for the implementation of the study. The other major authors and analysts were Gilbert Brunet and Bo Li (EDF), and Franz Bauer (VGB PowerTech).

Approval for the project was given by the Chinese National Energy Administration (NEA), without which it could not have gone ahead. The authors and analysts engaged in the study express their gratitude to NEA for appointing the China Electricity Council (CEC) as the IEA primary Chinese partner in the project. While CEC's Yiqing Cai (蔡义清), Xiaojun Chai (柴晓军) and Jianfeng Li (李建锋) took lead roles in the project, support also came from management and staff at the CEC Service Centre for Technology Development, particularly Yufeng Gang (江宇峰), Yong Luo (罗勇), Bin Li (李), Jianhua Mi (米建华), Haitao Huang (黄海涛), Jianghua Sheng (盛建华), Jihong Hao (郝继红), Xing Ji (吉星), Huimin Ji (冀慧敏) and Dongye Liu (刘冬野). Appreciation is also extended to the management and staff of the power plants that underpinned the project.

The authors are grateful to EDF and its China Division for providing technical, logistical and administrative support. While Gilbert Brunet and Bo Li (李博) played central roles in the project, thanks also go to Olivier Fages, Pierre Wang (王安胜), Didier Banner, Ying Luo (罗颖), Peile Shi (史培), Pierre-François Leporho and Jinwen Yang (杨锦文).

Colleagues at the IEA who contributed at various stages to the success of the project include Ulrich Benterbusch, Bo Diczfalusy, Carlos Fernández Alvarez, Jean-François Gagné, Stephen Gallogly, Dagmar Graczyk, Yuan Qin, Jonathan Sinton, Misako Takahashi, Kevin Tu and László Varró.

Special thanks go to Rebecca Gaghen and Muriel Custodio, and to Jane Barbière, Astrid Dumond, Angela Gosmann and Therese Walsh, who were instrumental in bringing the manuscript to publication. Cheryl Haines helped to prepare the manuscript, which was skillfully edited by Justin French-Brooks. Thanks also go to other IEA staff that provided administrative and legal assistance to this project. They are Rachael Boyd, Rachael Briggs, Virginie Buschini, Katerina Rus, Catherine Smith, Elizabeth Spong and Hanneke van Kleeff.

The authors would also like to thank Andrew Minchener, who contributed to the initial drafting; Jin Wang (王静), who supported as interpreter on site visits; and Shengchu Huang's team at the China Coal Information Institute for translating the report into Chinese.

This publication would not have been possible without a generous voluntary contribution from the United Kingdom, through its Embassy in Beijing. Special thanks to Leo Geddes, Rachel Ambrose, Li Ling, Bryony Mathew, Shelly Nania, James Godber, Na Lin, Nan Luo, Sherry Ma, and Richard Ridout.

The individuals and organisations that contributed to this study are not responsible for any opinions or judgements contained within this publication. Any errors and omissions are solely the responsibility of the IEA.

# Executive summary

## Purpose of the project



Coal ranks second only to oil as the world's leading energy source and is the world's principal fuel for the generation of electrical power. Today, coal-fired power plants with a total capacity of 1 700 gigawatts ($GW_e$) produce over 41% of the world's electricity. Looking to the future, if no new policies are implemented, global demand for coal used in power generation is projected to rise by more than one-third by 2035 – and in China by almost 50%.

In light of rising international concerns over the build-up of greenhouse gases in the earth's atmosphere, and the fact that coal-fired power plants currently produce, on average, much higher carbon dioxide ($CO_2$) emissions per unit of electrical output than other types of power plant, the need for greater efficiency is clear. Coal-fired power plants around the world are also coming under close public scrutiny in the communities and urban areas where they are located as a result of their emissions of local pollutants, particularly sulphur dioxide ($SO_2$), nitrogen oxides ($NO_X$) and particulates.[1]

The negative side effects of using coal to generate electricity are significantly increased by the relatively low efficiency of much of the world's existing stock of coal-fired power plants. The global average efficiency of coal-fired power plants currently in operation is roughly 33%,[2] much lower than for power plants that rely on other fossil fuel sources and significantly lower than the 45% efficiency possible with modern, ultra-supercritical coal-fired power plants. Over the operational lifetime of a typical coal-fired power generation unit, each percentage point increase in efficiency results in reduced $CO_2$ emissions totalling many millions of tonnes. If coal-fired units currently in operation around the world could be upgraded to operate at an average of 42% efficiency, annual $CO_2$ emissions would fall by more than 2 billion tonnes. In addition, for each unit of electricity generated, higher efficiency coal-fired plants consume less fuel, emit fewer local pollutants, and use less water.

As the world's largest consumer of coal, China stands at the forefront of both the challenges and opportunities offered by efficiency improvements. In response, China is undertaking a major national energy efficiency improvement programme, which includes improving the thermal efficiency and environmental performance of its existing coal-fired power plants. This programme offers the possibility of reaping the benefits of reduced greenhouse gas (GHG) emissions, lower coal consumption and thus lower operating costs, improved air quality and reduced water usage. It is also an ideal opportunity to showcase the benefits of improving energy efficiency to a global audience.

For these reasons, the International Energy Agency (IEA) and China's National Energy Administration (NEA) approached the China Electricity Council (CEC) to work with IEA to identify achievements possible through the upgrading and retrofitting of older coal-fired power plants. The objectives were:

- to evaluate the efficiencies of two coal-fired power units in China

[1] The combustion of coal is also a potential source of heavy metal emissions, some of which can be damaging to health and have deleterious environmental effects. Increasing concerns about the effects of such pollutants has led to the introduction of emission standards in some jurisdictions, e.g. for mercury in the United States.

[2] Unless stated otherwise, efficiency values are reported on the basis of the fuel's lower heating value (LHV) and net electricity sent out, i.e. LHV, net.

- to present examples of the energy-saving goals that have been achieved
- to identify the scope for further improvements
- to disseminate the results of the study within China and to other countries with sizeable coal-fired power generation capacity.



## Approach

The project was implemented by a team of international and Chinese experts from the IEA, EDF, VGB PowerTech, CEC and technical specialists from the two Chinese power plants from which units were selected for assessment.

To provide examples of possible achievements, the performance of two 300 megawatt electrical capacity ($MW_e$) coal-fired power plant units, each more than ten years old, was assessed. Throughout this report the two plants are designated Plant A, located in Shandong Province, and Plant B, located in Jilin Province. Each plant comprised several pulverised coal-fired units, where the two units assessed were designated Unit A3 (at Plant A) and Unit B4 (at Plant B). Both units were fitted with drum boilers operating under subcritical steam conditions with temperatures of around 540°C, and with net design thermal efficiencies of 39%.

The two units, A3 and B4, were selected to broaden the potential to identify opportunities for performance enhancement; there was no intention to compare their performance.

Following completion of a questionnaire by plant personnel, the project team visited each plant to gain an appreciation of the layout and the operational arrangements. Detailed discussions were held with the respective plant management and engineering staff to ensure that all information was fully understood and provided on a consistent basis. While improvements already made to the units were recognised, an assessment of the potential for further reduction of $CO_2$ emissions and local pollutants was also undertaken.

## Overview of key findings

An assessment of the coal-fired power units, A3 and A4, showed that their respective energy performance was generally good, with improvements made in recent years having had significant and positive impacts for $CO_2$ reduction. Broadly speaking, the approach taken to increase efficiency has been to improve combustion performance and optimise boiler efficiency; to maximise energy conversion by optimising the steam cycle; to reduce auxiliary power consumption by upgrading various pumps, motors, drives and power supplies; and to ensure best practice in terms of operating philosophies, procedures and maintenance practices.

In each case, the plant operators were in the process of working their way through this approach. Potential improvements were considered on a case-by-case basis for implementation based on investment cost and payback time. In general, improvements undertaken would usually be expected to pay for themselves in two or three years. Savings would be realised in reduced fuel costs (for the same electrical output) and reduced maintenance needs.

Typically, depending on the number of hours operated and the composition of the coal, 300 $MW_e$ units emit around 1.5 million tonnes (Mt) of $CO_2$ per year.[3] At Plant A, modifications had already been undertaken that would typically reduce $CO_2$ emissions from Unit A3 by around

[3] Estimate based roughly on 5 500 hours per year operation, standard coal consumption of 350 grammes coal-equivalent per kilowatt hour (gce/kWh) (or efficiency of 35%), and use of coal with a carbon content of 70%.

25 000 tonnes per year (t/yr), with a further modification planned to reduce emissions by an additional 41 000 t/yr. At Plant B, the modifications made would typically reduce $CO_2$ emissions from Unit B4 by over 73 000 t/yr, with a further 46 000 t/yr resulting from the retrofit of the unit to operate in co-generation mode.[4]



While Unit A3 was operating with good boiler efficiency, the steam turbine was in need of a major overhaul. Unit B4, on the other hand, had benefitted from an overhaul of the turbine, but, as yet, the boiler efficiency had not been optimised. Thus, as a very broad estimate, for a power-only nominal 300 $MW_e$ unit, annual $CO_2$ savings could reach some 100 000 tonnes to 110 000 tonnes (around 6% to 7% reduction in $CO_2$ emissions). This assumes that the unit was over ten years old, had been well maintained but had not undergone a major upgrade, and would be operating for around 5 500 hours per year (or full-load equivalent). For a unit where conversion to operation in co-generation mode is possible, the additional annual $CO_2$ savings could be substantially higher, depending on the heat demand.

Although each individual modification may lead to a small incremental increase in efficiency, cumulatively they are substantial, with increases made of 1.8 percentage points for Unit A3 and 3.0 percentage points for Unit B4. During performance tests, the net thermal efficiency of both units following the upgrades and modifications was close to the design value of around 39%. In each case there was scope for further improvements, where Unit A3 would benefit from an overhaul of the steam turbine and Unit B4 from an improvement in boiler performance.

## *Drivers for further improvement*

The average efficiency of the Chinese coal-fired power plant fleet is increasing steadily through a combination of measures, notably the introduction of advanced design units with very high efficiencies, the upgrading of a large number of the existing, operational units, together with a substantial retirement programme for smaller, less efficient plants. In accordance with the Chinese government's energy and carbon emissions reduction initiatives, it will be important for the power companies to continue their efforts to improve overall performance. In this regard, the new emissions standards, which came into effect on 1 January 2012, will impact almost all coal power plants, new and old, irrespective of age and size. For existing operating power plants, this will necessitate by July 2014: upgrades to existing electrostatic precipitators (ESPs) and/or the inclusion of bag filters; the upgrade of flue gas desulphurisation (FGD) systems; and the introduction of $NO_X$ control, which in most cases will require selective catalytic reduction (SCR). These new emissions standards may well provide a further driver to optimise power plant efficiencies. Otherwise, upgrading plants with an array of equipment to control emissions of particulates, $SO_2$ and $NO_X$, would increase the plant's auxiliary power consumption and reduce net export of electricity to the grid – and result in an increase in $CO_2$ emissions per kilowatt hour (kWh) of electricity exported to the grid.

Another important factor is that China is considering the introduction of some form of carbon tax within the next three years. Pilot programmes for emissions trading have already been introduced. The plan is for the carbon tax to target power companies, providing them with a strong driver to reduce $CO_2$ emissions. As a consequence of an impending carbon tax, power companies might well set performance targets to be met by individual power plants. Similarly, the government's energy intensity reduction target of 16% for the period of the 12th Five-Year Plan (2011 to 2015) is also providing a strong driver to raise efficiency. This is a top-down

[4] Co-generation is the process whereby a fuel source, such as coal or natural gas, is used to produce both electrical and thermal energy. A co-generation plant is more efficient than a utility-operated central power plant, since thermal energy that would otherwise be wasted is captured for use. The result is a much more efficient use of fuel.

process, with the overall target divided into quotas allocated to each province, various energy-intensive industries, and companies. Ultimately, this too could result in individual power plants being given performance targets.

Progress continues to be made on improving the flexibility and efficiency of China's transmission and distribution assets, particularly the overall efficiency and the interconnections for transmission between the provinces.



For Chinese coal-fired power plants, dispatch is based on priority given to those plants with the lowest cost of electricity, which may not be the more efficient plants with the lowest operating costs. To reduce costs, generators may be tempted to use cheaper, poorer quality coal, reducing efficiency and raising emissions. Furthermore, to accommodate all power plants that are designated to generate electricity within a given time period and a particular geographic area, generators are often required to operate at part-load conditions for some or all of the allotted number of hours in a month. This can have an adverse impact on their thermal efficiency as indicated by the performance of Unit A3 and Unit B4. Both units operated at significantly lower efficiencies than those obtained in performance tests. This resulted in higher coal consumption and higher emissions. It is a major challenge for China and other countries to exploit fully the higher plant efficiencies that can be achieved.

## Applicability to other power plants

Although, in principle, the same approach may be taken to identify cost-effective measures to improve efficiency and reduce emissions, the potential for other coal-fired power plants to emulate the achievements made on Units A3 and B4 will depend on the age of a unit, its design, and its overall performance. In practice, the magnitude of emissions reductions would be technology-specific, would vary with unit size and would be determined on a case-by-case basis.

The types of improvement made to the two 300 $MW_e$ units addressed in this project would be broadly applicable to other units of similar capacity. To place that in a Chinese context, the combined capacity of 300 $MW_e$-class (300 $MW_e$ to 399 $MW_e$) pulverised coal-fired units operational in China is believed to be over 200 $GW_e$, representing over 660 units. However, as the large proportion of these units will already have been upgraded to some degree, a precise projection of the total $CO_2$ emissions that might be saved through thermal efficiency improvements would require a detailed assessment on a unit-by-unit basis.

Other countries or regions, e.g. Association of Southeast Asian Nations, Australia, the European Union, India, Russia and the United States, all have coal-fired fleets that are dominated by subcritical units. In many cases, there is no active national programme to improve the performance of their existing generation stock, and neither is their emissions legislation as stringent as that imposed in China.

## Other recommendations

Within the power sector of many countries, the expectation is that standards will continue to be tightened and regulations introduced to ensure better environmental performance from coal, covering local pollutants, $CO_2$ emissions and water consumption. In this regard, several practices are relevant to countries that utilise coal for power generation:

- Better quality control of coal supplies to power stations is necessary, and preferably an increased use of lower ash, washed coal, as this reduces heat losses due to the otherwise high quantity of inert material in the combustion process. Where coal has to be transported long distances, it also reduces energy losses that arise from the transport of rock and ash.

- Problems can arise from government regulation of the power price. Some consumers may be subsidised, with access to power at low prices or for free. Artificially lowered electricity prices can lead to the wasteful use of power by consumers, and this, in turn, can lead to a greater demand for coal and, consequently, greater $CO_2$ emissions. In overall terms, power plant profitability may be low or, in other cases, negative, to the point where either temporary or permanent interruption to generation can occur. The practice can also limit the level of funding that will be available to pay for efficiency and environmental performance improvements.
- Losses from transmission and distribution systems need to be kept to a minimum for a well-integrated national grid system.
- Power dispatch modes should allow the more efficient power plants to operate more regularly at higher loads, when thermal efficiencies are also higher.
- More stringent emissions standards generally lead to better, more efficient plant operation. Where tighter emissions standards have been introduced, effective monitoring and verification is essential, with heavy penalties for non-compliance.
- More efficient units consume less water. While it is important to reduce water consumption through the whole coal chain, from mining to utilisation, improving both the efficiency and operation of generation units can have a significant impact.

# Introduction

## Background



Coal is an important source of energy for the world, particularly for power generation. In fact, demand for coal has grown rapidly over the last decade, outstripping demand for gas, oil, nuclear and renewable energy sources. Anticipated growth in energy demand is likely to extend the growth trend for coal. This presents a major threat to a low-carbon future. To achieve a sustainable energy system, ways must be found to use coal more efficiently and to reduce its environmental footprint.

Collectively, large coal-fired power generation units in use around the world are major contributors to total $CO_2$ emissions and, consequently, offer a unique opportunity for reducing those $CO_2$ emissions through increased efficiency. While potential reductions in $CO_2$ emissions through efficiency improvements at coal-fired power plants are extensive, there are limits to what can be accomplished through efficiency alone. To make even deeper cuts in $CO_2$ emissions, either carbon capture and storage (CCS) or widespread substitution of coal with cleaner energy would ultimately be required. However, the longer it takes for CCS to become an attractive commercial proposition and for cleaner fuels to be deployed, the more urgent it becomes to achieve the $CO_2$ savings possible through raising the efficiency of coal-fired plants. In addition, the future retrofitting of CCS is only likely to be undertaken on coal-fired power generation units with a high base efficiency. For these reasons, where they are cost-effective, efficiency enhancements offer a “no regrets” approach to reducing carbon emissions to the atmosphere.

A state-of-the-art coal-fired power generation unit can, in favourable circumstances, achieve an efficiency of 45% (lower heating value [LHV], net).[5] This contrasts starkly with the average efficiency of coal-fired generation plants globally, which lies at around 33%. While the average efficiency in China was 37.2% in 2011 (Mao and Feng, 2012), the value is boosted by the substantial capacity of new, high-efficiency units installed over the past decade. Over the operational lifetime of a coal-fired unit, each percentage point increase in efficiency could result in $CO_2$ emissions savings of the order of millions of tonnes. Typically, over 25 years, a 1 percentage point increase on a 300 megawatt (MW) unit operating at 37% efficiency could save in the region of 1 Mt of $CO_2$. In addition, and importantly, for each unit of electricity generated, more efficient coal-fired generation units consume less fuel, emit fewer local pollutants, e.g. $SO_2$, $NO_X$ and particulates, and use less water.

The IEA makes projections based on an analysis and comparison of various energy scenarios, to demonstrate the many opportunities to create a more secure and sustainable energy future. In its *Energy Technology Perspectives 2012 (ETP 2012)* assessment, the IEA showed the impact that technology could have in reducing global $CO_2$ emissions (IEA, 2012). *ETP 2012* models three main scenarios (Box 1).

The 4°C Scenario (4DS) takes into account recent pledges by countries to limit emissions and step up efforts to improve energy efficiency. It serves as the primary benchmark in ETP 2012 when comparisons are made between scenarios. Projecting a long-term temperature rise of 4°C, the

[5] Unless otherwise noted, efficiency notations in this report are based on the LHV of the fuel and net output, i.e. LHV, net. LHV, unlike higher heating value (HHV), does not account for the latent heat of water in the products of combustion. European and IEA statistics are most often reported on an LHV basis. For coal-fired power generation, efficiencies based on HHV are generally around 2% to 3% lower than those based on LHV. Net output refers to the total electrical output from the plant (gross) less the plant’s internal power consumption (typically 5% to 7% of gross power).

4DS is broadly consistent with the *World Energy Outlook* New Policies Scenario through to 2035 (IEA, 2013a). In many respects, this is already an ambitious scenario that requires significant changes in policy and technology.



**Box 1 • *ETP 2012* scenarios**

The IEA *ETP* 2°C Scenario (2DS) describes how technologies across all energy sectors may be transformed by 2050 to give a 50% chance of limiting average global temperature increase to 2°C. It sets the target of more than halving energy-related CO2 emissions by 2050 (compared with 2009) and ensuring that they continue to fall thereafter. The 2DS acknowledges that transforming the energy sector, while vital, cannot alone provide the solution: the goal can only be achieved if CO2 and GHG emissions in non-energy sectors are also reduced. The 2DS is broadly consistent with the *World Energy Outlook* 450 Scenario through to 2035.

The model used for this analysis is a bottom-up TIMES (The Integrated MARKAL-EFOM System) model that uses cost optimisation to identify least-cost mixes of technologies and fuels to meet energy demand, given constraints such as the availability of natural resources. The *ETP* global 28-region model permits the analysis of fuel and technology choices throughout the energy system, including about 1 000 individual technologies. The model, which has been used in many analyses of the global energy sector, is supplemented by detailed demand-side models for all major end-uses in the industry, buildings and transport sectors.

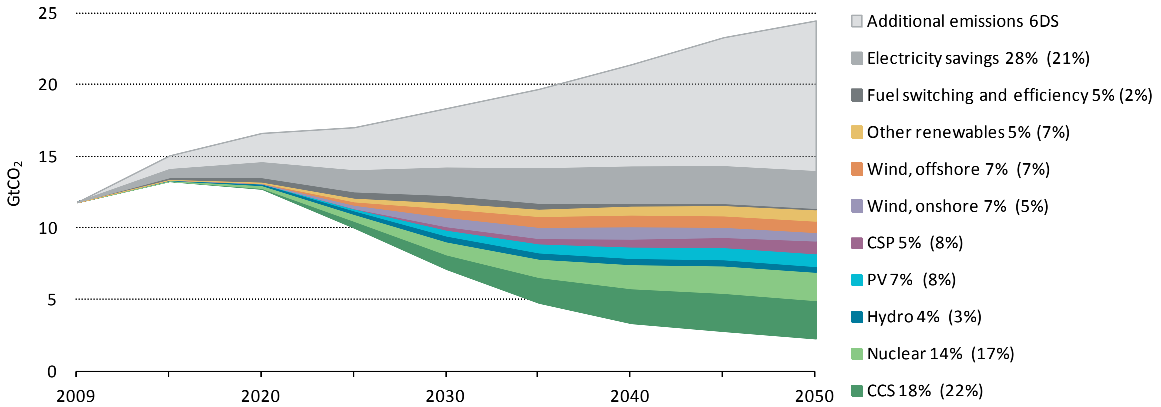
*ETP 2012* also considers 6°C and 4°C scenarios. The 6°C Scenario (6DS), the business-as-usual scenario, is largely an extension of current trends. By 2050, energy use almost doubles (compared with 2009) and total GHG emissions rise even more. In the absence of efforts to stabilise atmospheric concentrations of GHGs, the average global temperature is projected to rise by at least 6°C in the long term. The 6DS is broadly consistent with the *World Energy Outlook* Current Policy Scenario through to 2035.

IEA projections suggest that by 2035, under the 4DS, one-third of global electricity would still be generated from coal, with the net growth in coal-fired generation over the period from 2011 taking place in non-Organisation for Economic Co-operation and Development (OECD) economies (IEA, 2013a). Coal is abundant, widely available and affordable, which governments of emerging economies see as integral to ensuring the reliability and security of their energy supply. Globally, coal production and its contribution to power generation continue to grow. Major infrastructure continues to be built to ensure the steady production, transport and utilisation of this fossil resource on a global basis. At the same time, there is an increasing recognition that coal use must meet increasingly tighter environmental standards for emissions of conventional pollutants (particulates, $SO_2$ and $NO_X$), while also addressing growing environmental concerns over the carbon intensity of energy consumption by limiting emissions of $CO_2$. Global energy-related $CO_2$ emissions are over 33 gigatonnes (Gt) per year and must fall dramatically over the coming decades for a low-carbon energy future to be realised. Even meeting the 4DS could have a disastrous impact on the earth and its inhabitants.

With a focus on the power sector, Figure 1 indicates a possible $CO_2$ emissions trajectory under the 4DS and the contribution from various technologies and measures necessary to achieve the 2DS, i.e. to meet the goal of halving global energy-related $CO_2$ emissions by 2050 (compared to 2005 levels) on a least-cost basis (IEA, 2012). Note that the targets set out in China's 12th Five-Year Plan have already been assumed in the model.

A wide range of technologies will be necessary to reduce energy-related $CO_2$ emissions substantially. At the same time, where coal-fired power generation is concerned, it is evident that CCS will have the major role to play in reducing $CO_2$ emissions (see Box 2). However, as its introduction is not progressing as quickly as anticipated, the need to improve the efficiency of coal-fired power generation plant in the short to medium term is now urgent.

**Figure 1 • Key technologies for reducing global $CO_2$ emissions in the power sector in the 2DS, relative to the 4DS**




Notes: CSP = concentrated solar power; PV = photovoltaic; in the legend, the first percentage number for a technology refers to its share in cumulative $CO_2$ reductions between 2009 and 2050, while the percentage in parentheses refers to a technology's contribution in the annual reduction in 2050 from 14 Gt in the 4DS to 2.5 Gt in the 2DS.

Source: IEA (2012), *Energy Technology Perspectives 2012*, OECD/IEA, Paris.

**Box 2 • Potential of CCS**

CCS offers the means to achieve deep reductions in $CO_2$ emissions from coal-fired power plants and other large energy-intensive fossil fuel sectors. The CCS process comprises three integrated stages, namely:

- capture and subsequent compression of the $CO_2$
- the transport of the $CO_2$, usually as a supercritical/dense phase fluid
- its subsequent utilisation or injection into the selected geological formation.

The choice of capture technique depends on the particular technology used to generate power from coal, while the downstream transport and storage stages are essentially independent of the capture technique. All CCS options incur costs and reduce the efficiency of the plant. Fitting CCS to a power plant requires additional capital investment for the $CO_2$ capture and compression equipment, the transport infrastructure as well as the equipment associated with storage. In all cases, $CO_2$ capture will use additional energy for the capture and subsequent compression of the $CO_2$, reducing the overall process efficiency and also increasing the amount of fuel used to achieve a given power generation output. Consequently, the cost of capturing $CO_2$ will be lowest if this is done in large plants that operate at high thermal efficiencies and can best integrate the $CO_2$ capture process to limit, as far as practicable, the energy penalties.

The technique can be applied both to new plants, where the additional process equipment can be designed for maximum integration, and to existing plants as a retrofit application. In the latter case, key requirements are the need for adequate space at the power plant site to incorporate the additional equipment, which will be extensive, and the reasonable proximity of a $CO_2$ storage site.

Capital costs are expected to decline once this technology is demonstrated and then deployed on a significant scale. Improvements in the efficiency of the capture technologies, as well as effective integration with the other process components, will lead to reductions in the energy penalty. At the same time, other aspects, such as the reliability of the plant, scalability of the equipment, maintainability, as well as consumption of water, will need to be considered. The cost of CCS will also be affected by the length of pipeline between the power plant and the storage site as well as the type and depth of storage. Offshore storage would be more expensive than onshore storage.

Utilisation opportunities, such as using the $CO_2$ for enhanced oil recovery, may offset some of the costs of CCS. This may be particularly beneficial during the initial phases of demonstrating and establishing the technology, when the costs of CCS would be expected to be at their highest.

With regard to $CO_2$ mitigation by means of efficiency improvement, there are three ways to achieve this within the coal power sector, namely:

- to upgrade existing units to improve their thermal efficiency
- to ensure that new, larger units exhibit higher thermal efficiencies
- to close older, less efficient units where it is practicable to do so.



The majority of the global coal power fleet comprises mature, established plant designs, for which there is considerable scope to upgrade and ensure that performance is optimised. China has been particularly active in improving the efficiency and environmental performance of its coal-fired power plants, including the upgrading of existing units. Accordingly, following agreement from NEA, the IEA established a joint project with various partners (Box 3) to examine the efficiency improvements achieved and the potential for further improvements that could be applied worldwide.

**Box 3 • Objectives of the joint China-IEA study**

Numerous power plants worldwide have the potential to improve their overall performance by means of upgrade to allow them to operate close to or better than their original design performance. In many cases, there could be a strong return on investment from the costs incurred, especially with ever-tighter emissions legislation being introduced. The IEA aims to demonstrate the potential for upgrade and retrofit of coal-fired plants by using case studies from China. Such case studies could assist countries with a major coal component to improve the thermal efficiency of their coal-fired power plants to reduce CO2 emissions.

In recognition of the importance the Chinese government attaches to improving energy utilisation and the environmental performance of energy-intensive sectors, and the major achievements accomplished in coal-fired power generation, the IEA and NEA agreed to conduct this study. It represents an excellent opportunity to highlight some of the important measures the Chinese power sector has implemented at many of its coal-fired power plants and forms part of an IEA initiative to transfer knowledge to other coal-based economies.

The NEA appointed CEC as the lead Chinese technical organisation in the project. CEC selected two 300 MWe units for assessment. The project was implemented by a team of international and Chinese experts, drawn from the IEA, EDF, VGB PowerTech, CEC and technical specialists from the two power plants.

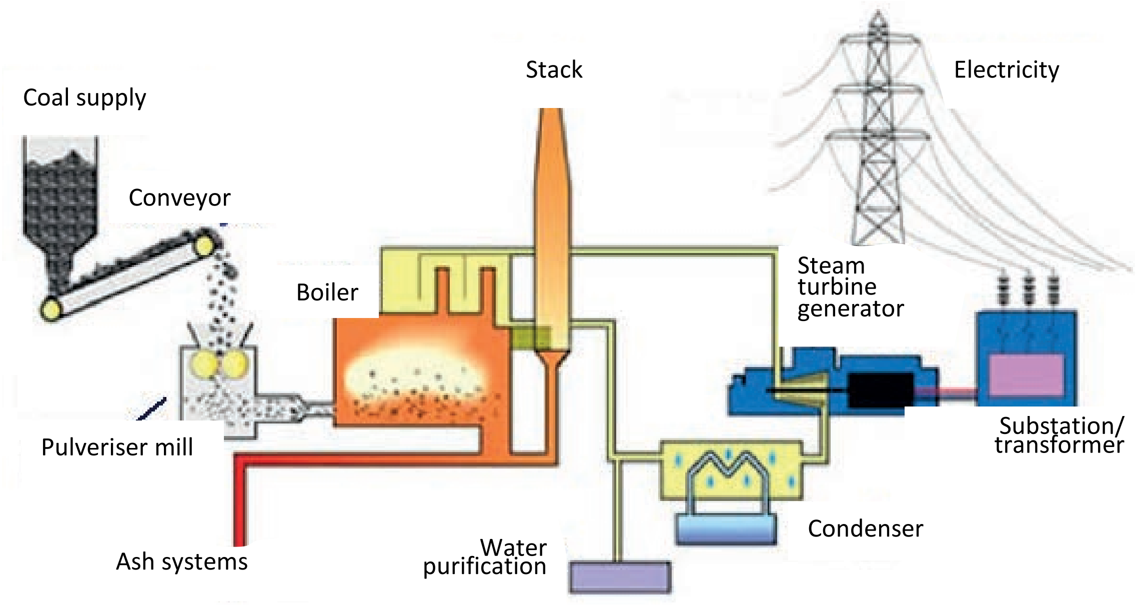
# Coal-fired power generation

## Overview of the process



While coal can be utilised for a wide variety of applications, it is primarily used for power generation. In 2011, 63% of coal produced was used to generate electricity (IEA, 2013a). The most common technology in use is pulverised coal combustion, which accounts for some 97% of coal-fired power generation capacity worldwide. Coal is first milled (pulverised) to a fine powder, which increases the surface area and allows it to burn more quickly. This is then blown with part of the combustion air through a series of burner nozzles into the combustion chamber of a boiler. Secondary and tertiary air may also be added to the combustion chamber. Combustion takes place at temperatures between 1 300°C and 1 700°C, depending largely on the type of coal used. The energy released heats the water in the tubes lining the boiler to produce steam. The high-pressure steam is passed into a turbine-generator, where electricity is generated and the steam is subsequently condensed before being returned to the boiler to be heated once again (Figure 2).

**Figure 2 • Schematic of the pulverised coal combustion power generation process**




Source: WCA (World Coal Association) (2014), *How is Coal Converted to Electricity?* WCA, London, www.worldcoal.org/coal/uses-of-coal/coal-electricity/ (accessed 5 March 2014).

The technology is mature and well understood, with thousands of units located around the world. Pulverised coal boilers have been built to match steam turbines, which currently have outputs between 50 $MW_e$ and 1 300 $MW_e$ although most new capacity has output rated at 600 $MW_e$ or larger to take advantage of economies of scale.

# Potential benefits of improved energy and environmental performance

Utility companies, in general, try to produce electricity at the most economic price while also meeting the environmental standards applicable to the size and location of the power plant. In most countries, the driver to increase the thermal efficiency of power generation (i.e. increase the amount of energy in the coal that is converted to electricity) is essentially economic. This entails a trade-off between the capital and operating costs involved, the risk element in the decision and the amount of additional energy converted. In broad terms, the higher the cost of coal, the greater the potential to reduce the overall cost of a new coal-fired power generation unit by increasing thermal efficiency and reducing consumption of fuel. This has certainly been the case in China, where there has been a major surge in the installation of new higher efficiency coal power plant with advanced steam conditions.

Driven by decreasing access to higher quality coal and a desire to reduce fuel costs, lower quality coal may be utilised. If at all possible, this course of action should be avoided because low quality coal is often characterised by both high ash content and high moisture content. A higher ash content increases heat losses in the combustion process, and energy is required to reduce the moisture content. Ultimately, the need to deal with both these issues leads to lower unit efficiencies. Independent of coal quality, washing coal prior to combustion is recommended; it not only reduces the ash content, but also the sulphur content of the coal.

Improvements in environmental performance are driven by the legal requirement to meet emissions standards. For the so-called conventional or local pollutants (particulates, $SO_2$ and $NO_X$), the inclusion of appropriate flue gas cleaning systems can meet all current requirements reliably and economically. These systems use well-proven technology such as ESPs or bag filters for fine particulates removal, FGD for $SO_2$ control, together with combustion modifications (such as low-$NO_X$ burners) and/or catalytic reduction systems for control of $NO_X$. Control systems for particulates and $NO_X$ emissions have a relatively small effect on the overall thermal efficiency of the power plant, while the inclusion of FGD can result in a 1 percentage point loss in thermal efficiency. The capital cost of these three measures can represent about one-third of the cost of a 300 $MW_e$ unit. For newer, larger units the cost is much lower, typically closer to 5%.

For a coal-fired power generation unit, the factor that links efficiency and environment is the increasing drive to limit $CO_2$ emissions, for which major reductions would require the deployment of CCS. However, increasing the thermal efficiency of converting coal to power is one of the less expensive ways of reducing $CO_2$ emissions. The average efficiency of all coal power stations in the world is currently about 33%, while new, advanced units can achieve up to 45% or better (depending on the feedstock, operating parameters and local conditions). Consequently, there is significant potential to reduce coal consumption and $CO_2$ emissions, with the expectation that efficiency improvements will continue to be made in the design of coal-fired power stations. Such efficiency gains represent the most cost-effective actions for reducing $CO_2$ emissions to the atmosphere, with the shortest lead time. Furthermore, deploying the most efficient plant possible is critical to enable such plants to be retrofitted with CCS in the future, since capturing, transporting and storing the power plant's $CO_2$ is currently a very energy and cost-intensive process.

Thermal power plants require substantial water volumes for the generation of steam and for ash process cooling. Improving the efficiency of a coal-fired power generation unit also reduces significantly the water consumption per unit of electricity generated.

# Measures to improve the energy efficiency of coal power plants

When considering measures to improve energy efficiency, a contrast is made between what can be done when designing a new coal power plant and what can be done to improve an existing plant by upgrading and retrofitting. For a new plant there is more scope for improvement, while constraints on existing plants, such as overall layout and availability of space for additional equipment, may be significant factors.



## *Options for achieving higher efficiencies with new plants*

At the design stage, there is a reasonable level of flexibility, with the following options all offering possibilities to raise efficiency.

### *Use of supercritical steam conditions*

A conventional (or subcritical) plant typically operates at temperatures up to 540°C and has a thermal efficiency of between 30% and 39%, depending on the unit size, coal quality and local conditions. To achieve higher efficiencies, supercritical (SC) and ultra-supercritical (USC) coal-fired technologies have been developed. At pressures above 22.1 megapascals (MPa), SC steam conditions are reached and, as temperatures exceed 600°C, steam conditions are said to be USC. SC units can achieve efficiencies up to 42% (LHV, net), while USC units can presently reach around 45% depending on the precise ambient and steam conditions.

For the future, new higher temperature alloys are being developed, with research and development (R&D) underway in China, Europe, India, Japan and the United States. The aim is to achieve steam temperatures of 700°C or higher, which would result in net thermal efficiencies approaching 50% or higher, although a considerable amount of work remains to be done, with commercial roll-out anticipated for the mid-2020s.

SC and USC plants have higher capital costs than conventional subcritical units because of the stricter specifications of the steel needed to withstand the higher pressure and temperature. However, this is offset to an extent by savings in fuel costs due to the higher efficiency of the process. In a higher efficiency plant, the coal consumption for a given electricity output is lower, while it also has a smaller footprint with respect to the central components, the size of coal handling facilities and its emissions control systems. Such efficiency improvements can make a significant impact, as a 1 percentage point increase in efficiency compared to a conventional coal-fired combustion plant results in a 2% to 3% reduction in $CO_2$ emissions. Thus, the more efficient USC coal plants emit close to 40% less $CO_2$ than the global average coal plant operating under subcritical steam conditions, as indicated in Figure 3 (VGB Powertech, 2012).

### *Inclusion of a second reheat stage on the steam turbine*

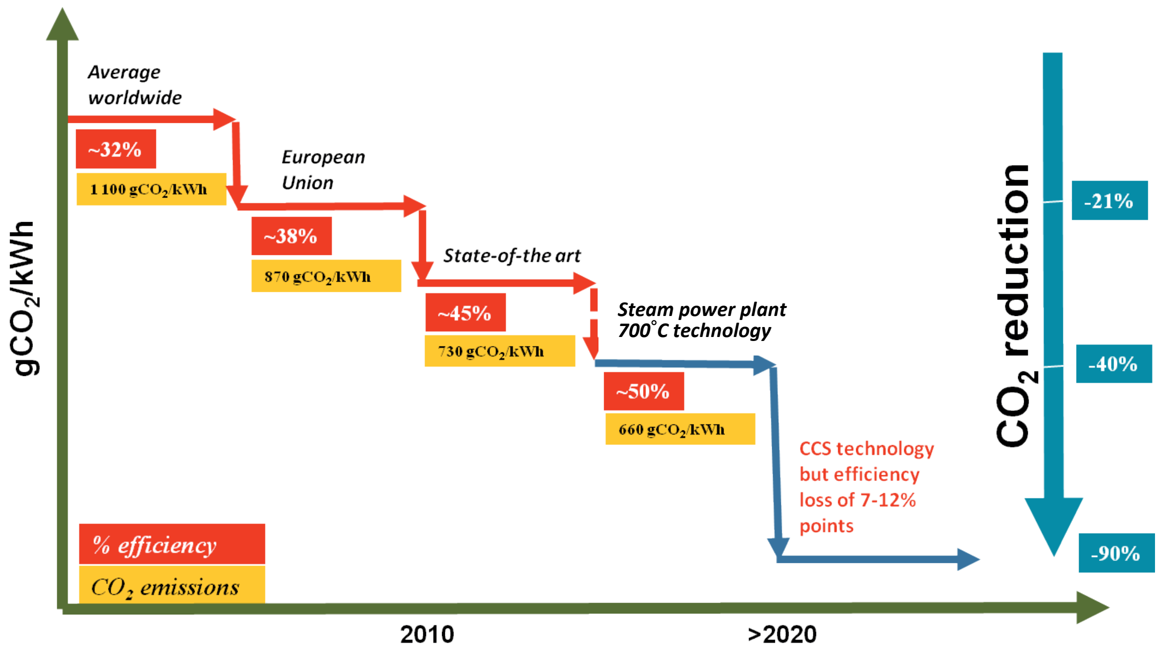
As noted above, the thermodynamic efficiency of a steam cycle rises with increasing temperature and pressure of the superheated steam that enters the turbine. It is possible to increase further the mean temperature of heat addition by taking back partially expanded and reduced temperature steam from the turbine to the boiler, reheating it, and then re-introducing it to the turbine. This can be done either once or twice, which is known as single and double reheat, respectively. The improvement in thermal efficiency can be 1 percentage point with the addition of the second reheat stage.

### Reduction in condenser pressure

Decreasing the condenser pressure from 0.0065 MPa to 0.0030 MPa can further increase the thermal efficiency by up to 1.5 percentage points (CIAB, 2010).



**Figure 3 • Indicative $CO_2$ emission reduction pathways**




Note: $gCO_2/kWh$ = grammes of carbon dioxide per kilowatt hour.

Source: Adapted from VGB PowerTech (2012), *Facts and Figures: Electricity Generation 2012/2013*, VGB PowerTech, Essen, www.vgb.org/en/data_powergeneration.html?dfid=55643.

### Reduction in excess air ratio

Reducing the excess air ratio from 25% to 15% can result in a small, but significant increase in thermal efficiency of 0.3 percentage points. Boilers are normally operated at the minimum practicable excess air ratio, while ensuring that sufficient air is available to burn virtually all the carbon present in the coal. At the same time, modern design and practice is to control and stage the addition of air in order to minimise the formation of $NO_X$ (otherwise known as air staging). Consequently, controlling the excess air is an important function in boiler operation, which requires a careful balance between these conflicting requirements (Schilling, 1993).

### Reduction in the stack gas exit temperature

Reducing the stack gas exit temperature by 10°C (while recovering the heat involved) can also bring about a similar increase in thermal efficiency of 0.3 percentage points.

## Options for improving the efficiencies of existing plants

Power plants are typically designed for a lifetime of between 25 and 35 years. It is not normally economic to retire plants prematurely and, in many countries, it is standard procedure to extend the life of a power plant to 40 years, with some units exceeding 50 years of operation. There has been much progress in plant life extension through refurbishing boiler parts, upgrading the turbines and adding flue gas cleaning to meet new emission regulations. Life extension is often possible due to the conservative nature of the original plant design and the fact that only a relatively small number of the components are life limited. Thus, while increases in national capacity may be met by the introduction of SC and USC plant, it is likely that the older, less efficient plant in the fleet would continue to dominate the capacity mix. Consequently, appropriate retrofitting of such units would improve their overall performance in terms of efficiency and emissions per unit electrical output. It is also important to recognise that, while the use of an SC or USC steam turbine is a potentially important route to higher efficiency, repowering (i.e. replacing a subcritical steam system with an SC alternative) is only technically viable on a unit that is at a capacity of at least 400 $MW_e$. For smaller units the steam flow through the high pressure turbine is too low to take advantage of the improved blade design.



The potential to improve existing units through upgrade and retrofit normally requires an exhaustive examination of the major functions – the combustion process, the steam cycle and major balance of plant equipment. The methodology used for this project is described in Annex A, while a broader discussion of measures to reduce energy consumption and increase efficiency is described in Annex B.

The impact of the retrofit approach will vary from country to country. In the United States, for example, the National Energy Technology Laboratory (NETL) of the US Department of Energy (US DOE) carried out a literature search of published articles and technical papers on potential improvements to existing coal-fired power plant efficiency (NETL, 2008). Efficiency improvement methods were identified for most components and systems, as summarised in Table 1. While it is unlikely that all of these improvements could be implemented at every plant, due to site-specific circumstances, the table does provide a useful indication of the significant potential for thermal efficiency improvement. In several cases, the suggested improvements offer potential efficiency increases of 1 percentage point or more.

**Table 1 • Potential efficiency improvements from measures to increase the efficiency of existing coal-fired power plants**

| Power plant improvements | Potential efficiency increase (percentage points) |
|---|---|
| Air preheaters (optimise) | 0.2 to 1.5 |
| Ash removal system (replace) | 0.1 |
| Boiler (increase air heater surface) | 2.1 |
| Combustion system (optimise) | 0.2 to 0.84 |
| Condenser (optimise) | 0.7 to 2.4 |
| Cooling system performance (upgrade) | 0.2 to 1.0 |
| Feedwater heaters (optimise) | 0.2 to 2.0 |
| Flue gas moisture recovery | 0.3 to 0.7 |
| Flue gas heat recovery | 0.3 to 1.5 |
| Coal drying (installation) | 0.1 to 1.7 |
| Process controls (installation/improvement) | 0.2 to 2.0 |
| Reduction of slag and furnace fouling | 0.4 |
| Soot blower optimisation | 0.1 to 0.7 |
| Steam leaks (reduce) | 1.1 |
| Steam turbine (refurbish) | 0.8 to 2.6 |

Source: NETL (2008), *Reducing $CO_2$ Emissions by Improving the Efficiency of the Existing Coal-Fired Power Plant Fleet*, DOE/NETL-2008/1329, NETL, Pittsburgh, PA, www.netl.doe.gov/energy-analyses/pubs/CFPP%20Efficiency-FINAL.pdf.

# Overview of coal power in China

Since 2000, China's economy has industrialised very rapidly and extensively, fuelled to a significant degree through the use of coal.



## Importance of coal power to the economy

Total power generation capacity has increased by more than a factor of three in the ten years to 2012 (Table 2).

**Table 2 • Annual power plant capacity and growth rate in China**

| Year | Installed capacity ($GW_e$) | Annual increase in capacity ($GW_e$) | Annual year-on-year growth rate (%) |
|---|---|---|---|
| 2000 | 315 | .. | .. |
| 2001 | 338 | 23 | 7.3 |
| 2002 | 357 | 19 | 5.6 |
| 2003 | 385 | 28 | 7.8 |
| 2004 | 442 | 54 | 14.8 |
| 2005 | 508 | 66 | 14.9 |
| 2006 | 622 | 114* | 22.4 |
| 2007 | 713 | 91* | 14.6 |
| 2008 | 793 | 80* | 11.2 |
| 2009 | 874 | 81* | 10.2 |
| 2010 | 970 | 96* | 11.0 |
| 2011 | 1 063 | 93* | 9.6 |
| 2012 | 1 147 | 84* | 7.9 |

* Net annual increase as some coal-fired plants close during each year.

Sources: Mao, J. (2011), "Ultra-supercritical technology – The best practical and economic way to reduce $CO_2$ emissions from coal-fired power plants", presented at the 7th International Symposium on Coal Combustion, Harbin, China (18-20 July); CEC (2013), *China Electricity Industry Annual Development Report*, CEC, Beijing.

In Table 3, capacity growth over the period from end-2003 to end-2012 is shown according to technology. The dominance of coal-fired power generation within the sector is clear. Although the share of coal has dropped a little, it still remains above 70%. The great majority of the annual increase in capacity was derived from the construction of coal-fired plants, of which some 5% are for co-generation applications (Mi, 2010). While hydropower capacity, which comprises much of the remaining capacity, doubled over the same period, its share was in steady decline. Other notable points are the small but steady increase in nuclear power and the new and rapid introduction of wind power as part of the government's initiative to reduce carbon intensity within the economy. However, in 2011, China's coal consumption reached 3.68 Gt (IEA, 2013), with 53% used for power generation.

A projection of China's total installed power generation capacity through to 2050 is shown in Table 4. The table draws on firm data for the situation at the end of 2011, the 12th Five-Year Plan for Energy (from 2011 to 2015), together with projections of the likely capacity mix for 2020 and 2050. The percentage of coal-fired power in China's electricity output should fall by about four percentage points by end-2015. On the same timescale, non-fossil energy is anticipated to comprise 32% of the total installed power plant capacity, up four percentage points over the level in 2010. However, because of the continuing growth in overall capacity driven by economic growth, although coal's share of the total will be lower, in absolute terms projections suggest it will increase significantly.

**Table 3 • Total installed capacity in China 2003-12 ($GW_e$)**

| | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|
| Total installed capacity | 385 | 442 | 508 | 622 | 713 | 793 | 874 | 970 | 1 063 | 1 147 |
| Coal | 286 (74%) | 320 (72%) | 373 (74%) | 467 (75%) | 538 (76%) | 583 (74%) | 632 (73%) | 660 (68%) | 734 (69%) | 783 (68%) |
| Natural gas | .. | 10 (2.4%) | 11 (2%) | 16 (3%) | 16 (2.2%) | 18 (2%) | 20 (2%) | 26 (3%) | 34 (3%) | 37 (3%) |
| Hydropower | 92 (24%) | 105 (24%) | 117 (23%) | 129 (21%) | 145 (20%) | 170 (21%) | 197 (22%) | 220 (23%) | 233 (22%) | 249 (22%) |
| Nuclear | 6.2 (2%) | 7.0 (2%) | 7.0 (1%) | 8.6 (1%) | 8.9 (1%) | 9.1 (1%) | 9.1 (1%) | 11 (1%) | 12.6 (1%) | 12.6 (1%) |
| Renewable power* | .. | .. | .. | 0.7 (0%) | 4.7 (1%) | 12.2 (2%) | 16.1 (2%) | 33.0 (3%) | 48.3 (5%) | 61.4 (5%) |

* Comprises on-grid wind and solar power plus a small proportion of biomass-fired units.

Note: .. = value not available.

Sources: CEC (2013), *China Electricity Industry Annual Development Report*, CEC, Beijing; Mao, J. (2011), "Ultra-supercritical technology – The best practical and economic way to reduce $CO_2$ emissions from coal-fired power plants", presented at the 7th International Symposium on Coal Combustion, Harbin, China (18-20 July); Zhu, F., S. Wang and H. Li (2010), *The Current Status and Prospect of Air Pollution Control for Power Sector in China*, http://apiperu.com.pe/argentina/trabajos/ECC_241_ZHU_Fa_hua.pdf.

**Table 4 • Projection for China's total installed power generation capacity for 2015-50 ($Gw_e$)**

| | 2011 | 2015 | 2020 | | 2050 | |
|---|---|---|---|---|---|---|
| | | Target | 4DS | 2DS | 4DS | 2DS |
| Total installed power plant capacity | 1 063 | 1 490 | 1 855 | 1 815 | 3 587 | 3 616 |
| Coal | 734 (69%) | 960 (64%) | 947 (51%) | 882 (49%) | 734 (20%) | 530 (15%) |
| Natural gas | 34 (3%) | 56 (4%) | 125 (7%) | 128 (7%) | 661 (18%) | 365 (10%) |
| Oil | 11 (1%) | x | 15 (1%) | 11 (1%) | 7 (0%) | 2 (0%) |
| Hydropower | 233 (22%) | 290 (19%) | 372 (20%) | 364 (20%) | 462 (13%) | 473 (13%) |
| Nuclear | 13 (1%) | 40 (3%) | 62 (3%) | 66 (4%) | 184 (5%) | 251 (7%) |
| Renewables | 48 (5%) | 148 (10%) | 335 (18%) | 364 (20%) | 1 538 (43%) | 1 996 (55%) |

Notes: x = not applicable; the data for 2011 are from CEC's *China Electricity Industry Annual Development Report*, 2013; the data for 2015 represent the official goals of China's 12th Five-Year Plan (2011-15); the projections of China's total installed power capacity for both the medium term (2020) and the long term (2050) are from the IEA's *ETP 2014* analysis for the 4DS and 2DS.

Sources: CEC (2013), *China Electricity Industry Annual Development Report*, CEC, Beijing; NEA (2013), 12th Five-Year Plan for Energy, State Council, Beijing; IEA (2014b), Energy Technology Perspectives 2012, OECD/IEA, Paris.

Projections for 2020 onwards are based on IEA analysis for its 4DS and 2DS scenarios (IEA, forthcoming b). In 2020, the 4DS projects 41% non-fossil capacity and the 2DS 44%. In 2050, the shares of non-fossil capacity shift to 61% (4DS) and 75% (2DS).

According to the government's indicative target, China's annual power consumption is anticipated to be 6 150 terawatt hours (TWh) by 2015 (NEA, 2013), with an annual growth rate of 8% from 2010. By 2020, electricity consumption is projected to grow to 7 132 TWh (2DS) and 7 513 TWh (4DS).

# Thermal power plant efficiency improvements

In 2000, China's coal-fired power fleet largely comprised small, old and inefficient units with limited emissions control systems. Since then, however, not only has there been a substantial year-on-year increase in the number of units, but there has also been a transformation in the performance of its fleet, especially since 2004. China has installed some of the largest, most advanced coal-fired units in the world, incorporating modern $SO_2$, $NO_X$ and particulate control systems. In particular, during the period of the 11th Five-Year Plan (from 2006 to 2010), considerable emphasis was placed on improving coal power plant efficiency. This was achieved by:

- introducing larger, high-efficiency units with advanced steam conditions
- closing 77 $GW_e$ of small, inefficient power plants, of which each unit was 100 $MW_e$ or less
- improving its fleet of 200 $MW_e$ to 300 $MW_e$ units to raise their thermal efficiencies.

The introduction of larger, high-efficiency units formed part of the overall plan to reduce energy intensity. In 2006, the National Development and Reform Commission (NDRC) declared that it would only approve new coal-fired plants with a capacity of 600 $MW_e$ or larger, with SC or USC steam parameters. The only exceptions were circulating fluidised bed combustion (CFBC) units that were introduced to burn low-grade coal or coal wastes, which could be smaller and less conducive to higher steam conditions, and co-generation schemes where the preference would be to seek economies of scale and to install 300 $MW_e$ units. Moreover, depending on local circumstances, smaller units could be approved.

At the time of this announcement by NDRC, a surge of orders came forward for smaller subcritical power units to be built, which gained belated approval and have added to the capacity mix. Consequently, in the period from 2007 to 2010 some 400 $GW_e$ of new power plant capacity was ordered, of which 82% was for SC/USC units, while the remainder comprised 13.2 $GW_e$ of 600 $MW_e$ and 62.5 $GW_e$ of 300 $MW_e$ subcritical units (Mao, 2011). Some of these units would begin operation during the period of the 12th Five-Year Plan.

At the same time, NDRC initiated its "Large Substitutes for Small" (LSS) initiative in which any power company seeking permission to increase its installed coal-fired power generation capacity had to agree to close some of its smaller, less efficient capacity.[6] The amount to be closed was calculated according to a formula provided by NDRC, which encouraged the construction of large units with advanced steam conditions. Thus, in order to build a new 600 $MW_e$ unit, some 420 $MW_e$ of old capacity had to be closed, while for a new 1000 $MW_e$ unit, 600 $MW_e$ was to be closed (NDRC, 2007a). The intention was to "uncompromisingly" decommission some 50 $GW_e$ of small thermal units. The initiative was very successful with 77 $GW_e$ retired during the 11th Five-Year Plan and 20 $GW_e$ of closures planned during the 12th Five-Year Plan (NEA, 2013). In fact, under the LSS initiative, close to 100 $GW_e$ of capacity has already been retired since 2006 (IEA, forthcoming a).

At present, the largest units in China have a capacity of 1 000 $MW_e$. An important point to note, however, is the need for China to incorporate a range of unit sizes to aid grid stability. The proportion of very large units must be related to the size of the provincial grid because of the disproportionate effect such a unit could have on the distribution system if it were to unexpectedly shut down. The need for smaller subcritical units is expected to decrease upon completion of measures to improve the operational flexibility of the grid network.

[6] Smaller capacity units are generally defined as units with capacity equal to or smaller than 100 $MW_e$. Less efficient units refer to those units that are no longer able to achieve their design efficiencies or whose design efficiencies are significantly lower than best practice units operating under the same or similar steam conditions.

In overall terms, during the period of the 11th Five-Year Plan, the average thermal efficiency of China's coal fleet improved from a coal consumption of 370 gce/kWh to 335 gce/kWh,[7] with the most modern, advanced units achieving less than 280 gce/kWh. The 12th Five-Year Plan for Energy stated a target of 323 gce/kWh by 2015 (NEA, 2013). According to CEC's China Electricity Industry Development Report 2013, the average efficiency of China's coal-fired power fleet reached 325 gce/kWh in 2012.

Alongside these efficiency measures, the Ministry for Environmental Protection (MEP) had already taken steps in 2003 to bring about major pollutant discharge reductions through the introduction of improved ESPs for fine particulate emissions control, together with the extensive provision of FGD for $SO_2$ control on most existing and all new coal power plants (Minchener, 2010). These requirements were made legally enforceable in 2006.

Complementary to initiatives for individual power plants, the NDRC has also explored options for improving dispatch capability within China. At present, there are two national grid companies, the State Grid and the Chinese Southern Power Grid, which between them own the various provincial grid systems. While the links between provinces have been improved, the ability to transfer power from one province to another is not yet optimal. In consequence, each grid company plans its power dispatch somewhat in isolation from the others.

Based on guidance from the provincial Development and Reform Commissions (DRCs), the relevant provincial dispatching centres belonging to the two power grid companies agree with each generator the specified number of operating hours per year. For example, a particular operating plant or unit may be awarded 5 000 hours full-load operation (or equivalent) per year. This is then allocated on a monthly basis by the company, which could then choose to operate the unit at full load for the hours nominated or for a greater number of hours at part load. To accommodate all power plants that are available to operate often means that generators are required to operate at part-load conditions for some or all of the allotted number of hours in a month.

With regard to dispatch decisions, the provincial grid company schedules a month-long load curve according to historic patterns of use and load forecasts (RAP, 2008). Based on the types of plants available, their allotted hours of operation and the projected load curve, the dispatchers schedule the generation for each plant. Generally, the position of different plants in the dispatch order is set according to the following guidelines:

- Base load is served by nuclear, non-dispatchable hydropower plants, co-generation facilities and the coal-fired units with lowest average total cost (which may not be the more efficient units with the lowest operating costs).
- Shoulder load is served by hydropower plants that have some flow controls and by intermediate-cost coal-fired plants.
- Peak load is served by pumped-storage units, fully-dispatchable hydropower units and the higher average total cost coal-fired plants.

These power plant dispatch policies are considered inherently inefficient, with the inefficiencies exacerbated by the lack of flexibility to transfer power from one provincial grid to another, resulting in a higher consumption of coal than is necessary and, consequently, higher emissions.

Since 2007, NDRC has carried out trials to establish an "Energy Efficient and Environmentally Friendly Power Generation Scheduling" approach, with the ambition to replace the current

[7] 370 gce/kWh is equivalent to 33.2% thermal efficiency, 335 gce/kWh to 36.7%, and 280 gce/kWh to 43.9%. These values are based on a lower heating value of standard coal of 7 000 calories per kilogramme (kcal/kg) (or 29.31 gigajoules per tonne).

system with one that is energy efficient and designed to support the use of lower-carbon power generation (NDRC, 2007b). With this approach, all grid-connected generating units would be placed in priority categories (PlanetArk, 2007) as follows:



- non-adjustable wind power, solar power, ocean power and hydropower
- adjustable hydropower, biomass, geothermal power and solid waste-fired units
- nuclear power
- coal-fired co-generation units and units for the comprehensive use of resources, including those using residual heat, residual gas, residual pressure, coal gangue,[8] coal bed methane and coal mine methane
- natural gas and coal gasification-based combined cycle units
- other coal-fired generating units, including co-generation without heat load
- oil and oil product-based generation units.

Within each category, units would be ranked according to their energy efficiency. Better-performing units would be ranked higher. Units with the same energy efficiency would then be ranked according to their emissions levels and water usage – where those with lower emissions and consuming less water would be ranked higher. Individual units would be scheduled for generation only when all units in higher categories and ranks were operating at full capacity. Based on the current and projected capacity mix, the expected impact would be that all grid-connected renewable, nuclear and gas-fired units would be operated at full capacity, with the expectation that the planned increases in capacity as set would also operate in the same way. For coal-fired units, some would operate at full capacity and others at less than full capacity depending on their position in the energy efficiency merit order. A positive consequence of this scheduling arrangement could be that power generation companies would choose to install new coal-fired generating units that are as large and efficient as possible to avoid being ranked below the cut-off boundary. In theory, this would accelerate energy efficiency improvement in the sector.

However, there are questions as to how NDRC might reform the electricity pricing mechanism with this arrangement and, while a trial was undertaken in Southern China during late 2007/08, no information is forthcoming on how well the implementation measures and operational plans worked, and it is unclear if this approach will be implemented nationwide.

These initiatives are being continued in the 12th Five-Year Plan (2011 to 2015) with efforts to meet key targets such as reductions in energy intensity of 16% and carbon intensity of 17%, relative to 2010 levels. China's target for coal-fired power generation is to achieve an average thermal efficiency of 323 gce/kWh (38.0%) by 2015 and 320 gce/kWh (38.4%) by 2020 (Mao, 2011). The intention is to build a further 300 $GW_e$ of coal-fired power generation capacity by 2015 (NEA, 2013), which would comprise predominantly 660 $MW_e$ or 1000 $MW_e$ high-efficiency SC and USC units. The government will continue to reduce the capacity of outdated power plant, with the closure of a further 20 $GW_e$ by end of 2015. The focus will be on the 100 $GW_e$ of inefficient plant, with unit size less than 200 $MW_e$, which represents about 18% of current total capacity (CEC, 2013). The 12th Five-Year Plan for Energy set mandatory reduction targets for particulates of $SO_2$ and $NO_X$ that will require that modern, very high-efficiency emissions control systems are installed on all new plant and on all existing units not scheduled for closure (NEA, 2013).

[8] Coal-gangue is a by-product of coal production. It is composed of a variety of solid wastes, with a heat content of between 2.09 megajoules per kilogramme (MJ/kg) and 6.27 MJ/kg and a carbon content of 6% to 20%.

In addition, having learned from its experiences during the 11th Five-Year Plan period, the MEP plans to ensure effective monitoring, verification and control such that acceptable implementation and compliance can be achieved within these sectors. This approach would also be compatible with the introduction of NDRC's "Energy Efficient and Environmental Friendly Power Generation Scheduling" since that, too, would require all thermal power generating units to be fitted with on-line thermal monitoring and continuous emissions monitoring devices.



**Table 5 • Capacity mix for coal-fired power plants at the end of 2012**

| Capacity | Number of units | Total installed capacity ($GW_e$) |
|---|---|---|
| All plants from 24 major power companies in China | 1 842 | 623 |
| Unit ≥ 1 000 $MW_e$ | 58 | 58 |
| 600 $MW_e$ ≤ unit < 1 000 $MW_e$ | 397 | 247 |
| 300 $MW_e$ ≤ unit < 600 $MW_e$ | 740 | 239 |
| 200 $MW_e$ ≤ unit < 300 $MW_e$ | 201 | 42 |
| 100 $MW_e$ ≤ unit < 200 $MW_e$ | 223 | 30 |
| 60 $MW_e$ ≤ unit < 100 $MW_e$ | 223 | 6 |

Note: Table includes data compiled from 24 companies by CEC. Although the majority of plants will be captured in the survey, it is not an exhaustive compilation of coal-fired units in China.

Source: CEC (2013), "China Electricity Industry Annual Development Report", CEC, Beijing.

Based on an extensive survey of China's coal-fired plants, it is considered that almost 40% were SC or USC by the end of 2012 (Table 5). This share will increase further over the next decade as an increase of around 270 $GW_e$ of SC and USC capacity is expected during the period of the 12th Five-Year Plan, while smaller subcritical units will continue to be closed.

The government's core size range for its coal-fired power fleet will comprise units from 300 $MW_e$ to 1 000 $MW_e$ capacity and, in due course, 1 320 $MW_e$. This represents a combination of highly efficient, modern units together with other smaller, but still "reasonably" efficient units that are not particularly old in the context of a 40-year lifetime. In recent years, the government has initiated various efficiency improvement programmes to complement the introduction of larger plants with advanced steam conditions, with a focus on improving the performance of the existing fleet of 300 $MW_e$ units (see Annexes A and B).

# The project

This project was implemented by the IEA to investigate the environmental benefits achievable by upgrading and retrofitting existing coal-fired power generation units. Increasing the efficiency of a unit can lead to reduced emissions, lower coal consumption and less water usage. Recognising China's programme on energy efficiency improvement, the IEA felt the project offered an opportunity to showcase the benefits and achievements to a wider audience. The methodology and approach to the project are outlined in Box 4.

**Box 4 • Methodology and approach to the project**

**Methodology**

- Evaluate the efficiencies of selected coal-fired power units
- Ascertain the energy-saving initiatives that have been undertaken
- Identify the scope for further improvements
- Establish the dissemination potential within China and other countries with a significant coal-fired power capacity.

**Approach**

- International experts formulated and, with China Electricity Council, agreed upon a questionnaire for submission to representatives of two selected power plants. The questionnaire was wide-ranging and covered all key aspects of the plants, including the provision of basic technical design data, operational records, mass and energy balances, and emissions data and performance figures.
- The power plant personnel prepared responses to the requested information.
- The international experts, CEC and the IEA visited each plant to gain an appreciation of the layout and the operational arrangements.
- Discussions were held to address questions that arose from the plant visits and to ensure that responses to information requested in the questionnaire were provided on a consistent basis and were fully understood by all parties.
- The international experts and CEC prepared a joint report that presented detailed comments on the overall energy and environmental performance of each plant, together with an assessment of the potential to reduce the emissions of CO2 as well as other pollutants, such as NOX, SO2 and particulates.

## Basis for selection of Chinese power plants for audit

In accordance with the Chinese energy efficiency initiatives, it was decided to assess the performance of two coal-fired power units, each with over ten years of operation, and each at the lower end of the core capacity range. Thus, they were both expected to remain operational for a further 30 years or so, and, consequently, there could be considerable merit in optimising performance. Following discussions with CEC and its members, two units were selected, one located in Shandong Province and the other in Jilin Province. They were designated Unit A3 at Plant A and Unit B4 at Plant B, respectively. Both units selected were nominal 300 $MW_e$ units with characteristic drum boilers and subcritical steam temperatures of around 540°C and with net design thermal efficiencies of 38% to 39%. A range of efficiency improvements had already been undertaken on the two units in line with the policies outlined above.

## Results obtained

While the key results from the project are discussed below, more detailed findings are described in Annex B.

## Overview of key findings

The assessment of the two nominal 300 $MW_e$ units showed their respective energy performance to be generally good, with the improvements made in recent years having had significant and positive impacts. Not only had the actions reduced the overall costs of power generation, they also resulted in lower levels of $CO_2$ being emitted.

It is important to recognise that the plants were built to a design and at a time when optimising efficiency was not a priority. Coal prices were comparatively low and environmental emissions were not so tightly controlled. Less attention was given to achieving a performance close to the design value. For example, in 2004, the typical net efficiency of a 300 $MW_e$ unit was 36%, even though most were operating at or close to maximum achievable output (Zhao, 2004). In contrast, Units A3 and B4 achieved efficiencies close to 39% under standard test conditions. It should be noted that such improvements have been implemented on most 300 $MW_e$ units operating in China during the 11th Five-Year Plan period (2006 to 2010).

At the same time, environmental standards are becoming tighter, and the cost of coal for power generation has risen significantly. Consequently, it will be important for power companies to continue their efforts to improve and maintain unit performance while meeting new regulations and standards.

The dispatching mode is also important because a power plant operates best at high load and on a continuous, steady-state basis. In the case of Units A3 and B4, both units had operated at part load for long periods of time, which has had an adverse impact on their thermal efficiency. This is evident from the data presented in Annex D, where monthly data obtained during the early part of 2011 for both units demonstrate significantly lower efficiencies compared to the values obtained during the performance tests.

## Likely $CO_2$ emissions reductions that can be achieved

As a result of the improvements made by the Chinese engineers, the projected annual savings of $CO_2$ emissions were just over 25 000 tonnes for Unit A3 and around 120 000 tonnes for Unit B4.

To put these values in context, Unit A3 was operating with strong boiler efficiency, but the steam turbine required a major overhaul, while Unit B4 had benefitted from a turbine overhaul but, as yet, the boiler efficiency had not been optimised. Also, the latter unit had been converted to a co-generation application, which provided a high proportion of its $CO_2$ savings.

Thus, as a very broad approximation, for a power-only nominal 300 MWe unit that was a little over ten years old, one that had been well maintained but had undergone no prior major upgrade, possible annual $CO_2$ savings could be in the region of 60 000 tonnes to 70 000 tonnes, assuming that the plant operates at steady-state, full-load output conditions. If the units were to be retrofitted to operate in co-generation mode, the annual $CO_2$ savings could be substantially higher – in some cases, more than 100 000 tonnes. With potential annual $CO_2$ emissions for each unit at around 1.5 Mt, such savings are significant, particularly if this is aggregated over their remaining lifetimes.

## Indicative payback periods for improvements

The basis of evaluating efficiency gains using cost-benefit analysis would be to establish a correlation between the costs of the efficiency measures, which are linked to both capital investments and operating costs, and possible revenues, including savings in coal consumption.

It is not appropriate to generalise on payback periods. Case-by-case studies are required as benefits are dependent on the structure of local costs, on the possible financing conditions available to the company and on the availability or otherwise of financial incentives either from national or provincial sources.

## Comparable studies



The project has shown that significant thermal efficiency improvements to existing 300 $MW_e$ coal-fired units have been achieved through the cost-effective introduction of a range of new and upgraded components. These findings are broadly compatible with those from other international studies that also examined the potential for upgrading and refurbishment of older coal-fired plants.

In 2005, the Asia-Pacific Economic Cooperation (APEC) Expert Group on Clean Fossil Energy undertook a study, based on data available up to end-2004, to assess a wide range of relatively small coal-fired power units (less than 300 $MW_e$) in a wide range of countries, including China, and with widely diversified cost structures and differing economic growth patterns (APEC, 2005). The group concluded that it would be technically feasible for 50% of the coal power plants in the APEC region, which includes China, to achieve a 3.5 percentage point $CO_2$ emissions reduction at negative or zero net cost – equivalent to net emissions savings of 165 Mt of $CO_2$ per year (Annex E).

The same year, the European Commission also commissioned a project that focused on coal-fired power plants in China (European Commission, 2005). Case studies were undertaken on two 200 $MW_e$ units, where the prospects for upgrades in equipment, the introduction of new equipment, and changes in procedures and operating philosophy were investigated. The project concluded that:

- Positive impacts could be expected from the introduction of a coal quality management system and the establishment of an operational management information system to optimise overall performance. These low-cost measures produce economic benefits through efficiency increases and improve the overall management of resources that normally leads to cost reduction.
- Devices for measuring coal and air mass flow rates, which were readily available, would have provided a promising method for significant improvement of combustion rate due to the possibility to adjust air flow into individual burners according to real demand.
- Computational methods for follow-up of boiler operation, together with process models, would allow optimisation of overall boiler operation, and give valuable information about the status of the process.
- Improved soot blowing offered savings in steam consumption, an increased super-heater temperature, and lower fuel and maintenance costs.
- Improvements in the air preheater to minimise leaks might require a re-build of the heat transfer elements but would raise combustion efficiency.

## Applicability to other power plants

As shown in Table 5, while the share of large units (greater than 600 $MW_e$) with advanced steam conditions in China's coal-fired power fleet is growing very rapidly, the bulk of its fleet is based on comparatively small units (up to 300 $MW_e$). The expectation is that, in accordance with government policies, there will be further extensive closures of the smallest units (less than 200 $MW_e$), with the core of the fleet comprising 300 $MW_e$ units and the larger, modern plant.

The applicability of the findings to other power plants in China would be defined by the age of the unit, the design of the unit and its overall performance. A detailed study of the Chinese coal-fired power sector and, ultimately, a site-specific review would need to be undertaken by the plant owners prior to actual engineering work being considered.

On a generic basis, improvements would comprise:

- optimisation of the combustion process to maximise energy release from the coal
- optimisation of the steam cycle to maximise the conversion of energy to power
- ensuring best practices in operating procedures and maintenance.



In principle, such an approach is directly applicable to all coal-fired power plants. In practice, the applicability of measures taken will be technology-specific and the quantifiable improvement will vary with unit size.

The improvements that have been applied to the two 300 $MW_e$ units investigated in this study should be directly applicable to other units of a similar size. To put that in context, the capacity of 300 $MW_e$ pulverised coal-fired units operational in China is believed to be over 135 $GW_e$, representing about 450 units, the larger part of which has already been upgraded. To provide an accurate projection of the potential to reduce $CO_2$ emissions further through thermal efficiency improvements, a detailed, case-by-case assessment by technical and engineering specialists would be required.

## *Other impacts on coal power plant efficiencies*

Most proposed improvements would be subject to a process of cost-benefit analysis as outlined above. Exceptions will occur when the government introduces specific requirements, where the only choice might be to make the investment or cease to operate. An issue that has impacted on almost all coal power plants in China, irrespective of age and size, was the need, from 1 January 2012, to meet the new emissions standards for particulates, $SO_2$ and $NO_X$. This will require, by July 2014, existing power plants to upgrade ESPs and/or install bag filters, upgrade FGD systems and introduce $NO_X$ control systems, which in most cases will require SCR. These new emissions standards may well provide a driver to optimise power plant efficiencies, as deploying additional emissions control systems increases auxiliary power consumption. Increasing plant efficiency reduces specific emissions, thereby reducing the footprint and cost of emissions control equipment.

Another important factor is the prospect of China introducing some form of carbon tax within the next three years. Expectations are that a relatively low rate of carbon tax (e.g. CNY 10 or USD 0.16) would be applied per tonne of $CO_2$ discharged by a business or other operation, with prime targets being producers of fossil fuel-based energy, such as power companies. The prospect of a carbon tax could provide an incentive for power companies to limit $CO_2$ emissions, perhaps by setting performance targets to be achieved by individual power plants.

Similarly, the government's energy intensity reduction target for the period of the 12th Five-Year Plan may provide a strong driver. This is a top-down process, with the overall target being divided among the provinces, the various energy-intensive industries and the companies. Ultimately, this too could come down to individual power plants being given targets that they would then be required to meet.

# Conclusions

The results of this study demonstrate the enormous potential for increasing the efficiency of coal-fired power plants, and how such upgrades can be accomplished in a manner that makes both economic and environmental sense. While this study focuses specifically on 300 $MW_e$ subcritical units, its broader lessons are applicable across the family of subcritical units as a whole. Furthermore, while this study addresses specific power plants in China, the results can provide valuable insights and guidance for countries and power companies around the world that are currently operating subcritical coal-fired power plants.

China is undertaking a major initiative to reduce its carbon and energy intensities while maintaining strong economic growth. Central to the initiative has been its strategy to lower the carbon intensity of its power sector. Over the past decade, but particularly since around 2006, the average efficiency of China's coal-fired fleet has been rising steadily. The fleet is being rationalised around units within a core capacity range of 300 $MW_e$ to 1 000 $MW_e$. Success in increasing the average efficiency of its coal-fired fleet owes much to a small number of discrete actions. Much of the coal-fired generating capacity added in recent years has consisted of large, high-efficiency SC and USC units that produce much more electricity per unit of coal consumed. An extensive programme to raise the efficiency and improve the performance of existing, operating units is in place. There has been significant progress on decommissioning the poorest performing power generating units; indeed, since 2006 China has retired close to 100 $GW_e$ of small, inefficient, coal-fired generating capacity.

The strategy to improve the performance of China's coal-fired power generation fleet has been particularly effective with respect to the nominal 300 $MW_e$ units that are the subject of this study. Because many of these power units are older and therefore were initially designed to operate at efficiency levels below current standards, the goal has been to improve performance, in many cases beyond the original design specifications. As shown in this report, such efforts can be not only successful but also cost-effective. Given the large number of similarly sized and vintage coal-fired power plants currently operating both within and outside of China, there are clear benefits to disseminating the findings of this report widely. The need for wider understanding of the benefits of efficiency upgrades is particularly strong for those older power plants that are neither performing to original design specifications nor scheduled for closure in the near future. While this report focuses on 300 $MW_e$ units, the findings can reasonably be expected to be applicable to the many older 200 $MW_e$ units, which are likely to be some of the least efficient still in operation.

Outside of China, there are many countries with existing, generally older coal-fired units that operate well below their design efficiencies. The lessons learned from this study on the value of upgrading components within the boiler, the steam turbine and the larger ancillary components should therefore be of interest well beyond China's borders, as should the results on the impact of adopting the most effective operational procedures and robust maintenance practices to maintain high operating efficiencies.

Within the coal-fired power sector, the expectation is that standards will continue to be tightened and inducements introduced to ensure better environmental performance, covering both conventional pollutants and $CO_2$ emissions. For example, new emission standards introduced in China at the start of 2012 apply to new and existing coal power plants. For the latter, almost all units will require extensive upgrade for fine particulate and $SO_2$ control, as well as the introduction of de-$NO_X$ systems on all plants not scheduled for closure. All of these steps are expected to be implemented by July 2014. There is also the expectation that a carbon tax may be introduced on a similarly rapid timescale. Both these regulatory measures would provide incentives for achievement of further efficiency improvements.

Outside of China's strategy of improving average fleet efficiency through upgrade, retrofit and improved operation, there are other factors that have a direct influence on plant performance. And as some other countries also experience these factors, it is important that they are recognised and addressed:



- Better quality control on coal supplies to power stations is warranted, together with increased utilisation of coal washing. Washing reduces the ash content, and, as heat losses in the combustion process arise from the higher levels of inert material in unwashed coal, ultimately leads to higher unit efficiencies. The sulphur content of the coal may also be reduced during the washing process. Hence, as well as reducing particulate emissions, the formation and release of $SO_2$ are also lowered.
- While the price of thermal coal is market-driven, the retail power price is tightly regulated in China. This mismatch between free and controlled pricing systems can result in a range of unwanted consequences. Keeping electricity prices artificially low can lead to wasteful use of power by consumers that, in turn, could lead to a greater demand for coal. This contributes to a destructive cycle in which the higher demand for coal carries the potential of pushing fuel prices higher and thus furthering weakening the normal market linkage between fuel costs and consumer energy costs. One pitfall of this destructive feedback loop between low consumer energy prices and rising fuel prices is that power plants operate at low or even negative margins, making it difficult or impossible for them to implement needed upgrades or to continue quality maintenance. At its most extreme, an imbalance between fuel costs and energy prices can cause power plants to close, resulting in interruptions to the electricity supply to the regions served by those plants. Just as importantly, the excessive and inefficient consumption of electrical power represents a drain on overall economic performance, increases the emissions of local pollutants and adds to rising $CO_2$ emissions.
- A fully integrated grid system covering the whole of China is required, with better connection between the State Grid and the Southern Power Grid. Improving power dispatch would enable more efficient power plants to operate optimally, i.e. more regularly and at higher load. Trials have been undertaken in China to assess the applicability of a merit order approach to dispatch, based on the more efficient, lower $CO_2$-emitting plants gaining preferential access to the grid. Now that tighter emissions standards have been introduced along with improved monitoring and verification, this approach offers even greater potential advantages. Given the experience gained by other countries in adopting such an approach, the potential exists for international collaboration with China to develop and deploy an integrated and flexible system applicable to the Chinese context.

# Annex A: Methodology and definitions

Methodology for energy saving for coal-fired power plants:

$$\eta_n = \eta_b \times \eta_t \times (1 - K)$$



$\eta_n$ unit net efficiency
$\eta_b$ boiler efficiency
$\eta_t$ turbine efficiency
$K$ auxiliary power consumption.

To improve the unit net efficiency $\eta_n$, three changes can be made:

- improve the boiler efficiency
- improve the turbine efficiency
- reduce the auxiliary consumption rate.

According to the indirect energy balance calculation formula for boiler efficiency:

$$\eta_b = 1 - (q2 + q3 + q4 + q5 + q6)$$

*q2* exhaust gas heat loss
*q3* heat loss due to unburned gases
*q4* heat loss due to unburned carbon in refuse
*q5* heat loss due to radiation
*q6* heat loss due to sensible heat in slag.

Auxiliary power consumption rate for production is defined as the ratio of power consumed by all necessary auxiliary equipment for power production compared to the total power generated, as follows:

$$Lcy = Wcy/Wf = (Wh - Wkc)/Wf$$

*Lcy* auxiliary power consumption rate for production
*Wf* total power generated during statistic period, kWh
*Wcy* auxiliary power consumed during statistic period, kWh
*Wh* total power consumed during statistic period, kWh
*Wkc* power deducted as per the regulation below.

The following are excluded:

- the power consumed during boiler warm-up, boiler chemical cleaning, turbine warm-up and idling operation for either new equipment or equipment returning to operation after major overhaul
- the power consumed for the commissioning of new equipment
- the power consumed either for planned outages or in civil works construction/modification
- the power consumed when the generator is used as a phase modifier
- the power consumed by transport tools outside the plant, such as a train or a ship

- the power consumed by the step-up/step-down transformers for power distribution (auxiliary transformers excluded), and by the phase modifier and wave modifier
- the power used by the workshops and all kinds of services (office, canteen, dormitory, school, hospital).



Comprehensive auxiliary power consumption rate:

This is defined as the ratio of the difference between the total power generated and the on-grid power compared to the total power generated, as follows:

$$Lzh = (Wf - Wgk + Wwg)/Wf$$

| | |
|---|---|
| *Lzh* | comprehensive auxiliary power consumption rate |
| *Wf* | total power generated during statistic period, kWh |
| *Wgk* | on-grid power, kWh |
| *Wwg* | power purchased from the grid, normally via the start-up transformer, kWh. |

# Annex B: Energy-saving measures used in the Chinese coal power sector



## Measures to improve boiler efficiency

### *Optimise the boiler combustion process*

The unburned carbon in fly ash and bottom slag and heat loss from exhaust flue gas can all be reduced by optimising both the pulverised coal fineness and excess air coefficient, together with adjustment of the primary air and combustion air parameters according to the coal quality.

In China, the coal market situation has proved very difficult in recent years, with the quality of the coal available to power plants being quite variable and on occasions deviating significantly from the design specification. The most positive impact could be achieved through the introduction of a coal quality management system, including a management information system, to optimise overall performance. These are low-cost measures that produce economic benefits through efficiency improvements. The alternative, which is commonly used in China, is to rely on the experience of the plant operators to control the combustion process, drawing on whatever information can be provided. At the very least, this requires that data on coal quality and unburned carbon in fly ash are made available to the shift teams, so that the operator can manually optimise the combustion process. As is indicated in the main report, this approach can give reasonable results.

### *Optimise heat transfer through proactive soot-blowing procedures*

Heat transfer can be optimised by applying proactive soot-blowing procedures. Soot blowers in the boiler need to be used on a regular basis as cleaning of super-heater and re-heater tubes will result in savings in steam and positively affect the heat balance. This also results in a lower flue gas exhaust temperature as well as prolonging times between maintenance shutdowns.

### *Reduce the heat loss from exhaust flue gas*

Reducing the temperature of the exhaust flue gas represents the main source of efficiency loss from the boiler. The following actions can be taken to improve the situation:

- reduce air leakage of the furnace, flue gas duct and milling system
- increase the mill outlet temperature depending on the coal characteristics
- adjust the primary air ratio according to the volatile content of the coal
- establish a robust soot-blowing procedure for the heat exchangers, including the air preheater
- reduce air leakage from the air preheater.

Since air leakage from the air preheater has a knock-on impact on the auxiliary power consumption of induced draft (ID) and forced draft (FD) fans, this is a major issue that is commonly addressed in Chinese power plants. As a guideline, an acceptable leakage rate is approximately 6%; if it is between 8% and 10%, then repairs will be undertaken during scheduled unit outage. When it is higher than 10%, a major overhaul is generally required, including retrofitting of new, improved sealing technology.

If the exhaust flue gas temperature cannot be reduced to an acceptable level, by a combination of the measures listed above, then the inclusion of an additional economiser or heat recovery system would need to be considered. This would represent a significant investment for which a typical payback period would be about five years, the exact value depending on factors such as likely fuel cost saving and interest rate on the loan.



# Measures to improve turbine efficiency

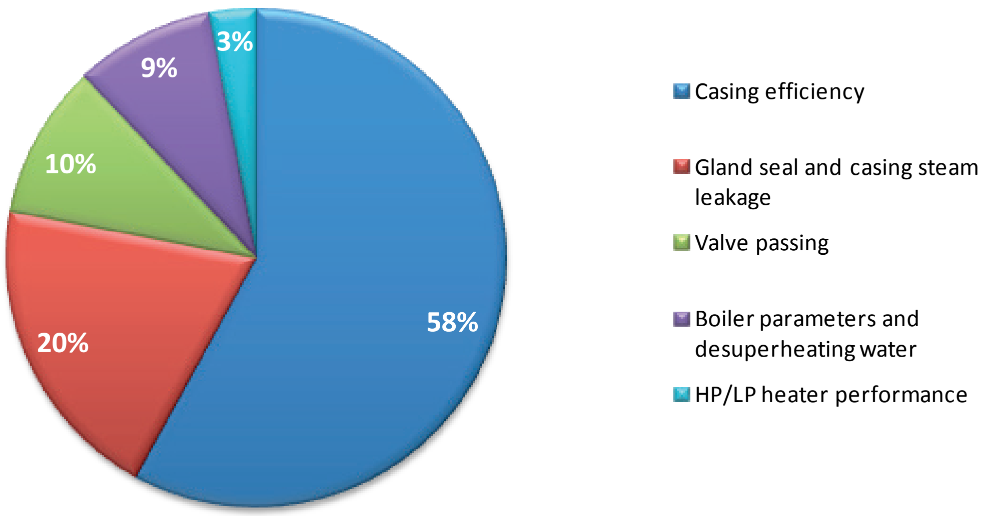
## *Restore turbine cylinder efficiency*

The degradation of the turbine casings' efficiency can be due to the following factors:

- ageing
- excessive clearance between the gland seal
- steam leakage from the inner cylinder joint
- steam passing/short circuiting between stages
- defects in the flow passage
- steam quality (wetness, silica, chemical conditioning).

An example of the key impact factors and their relative importance on the steam turbine heat rate are shown in Figure B1, which is based on an assessment of Unit A3 of Plant A in 2011.

**Figure B1 • Impact factors for the steam turbine in a 300 $MW_e$ steam turbine**



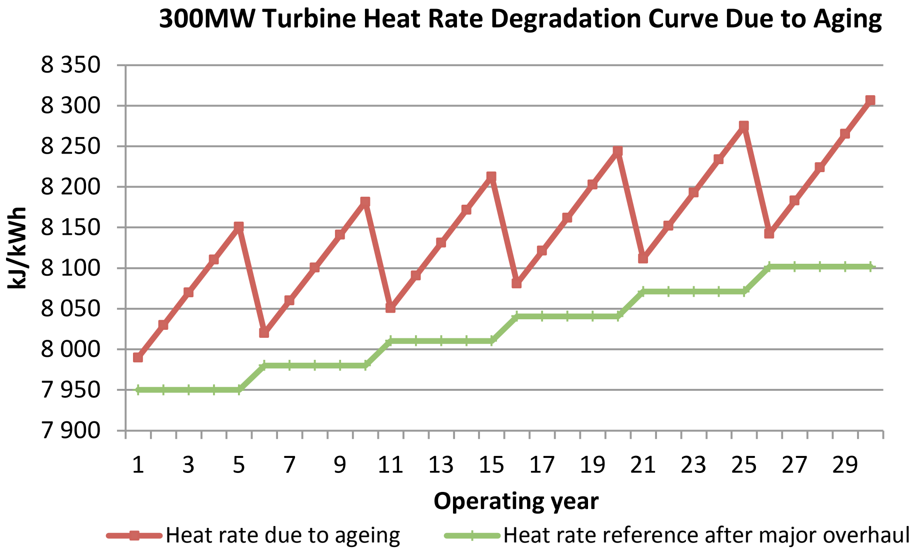

Note: HP = high pressure; LP = low pressure.

## *Correction for ageing*

Ageing is a normal occurrence and the typical annual impact on the turbine heat rate degradation is about 0.5%. When a major overhaul is implemented, some 85% of the heat loss can be recovered. As an example, for a 300 $MW_e$ turbine, with a turbine-driven boiler feed water pump, the design heat rate is 7 950 kilojoules per kilowatt hour (kJ/kWh). After five years of operation, this rate would increase to about 8 150 kJ/kWh due to ageing. After a major overhaul, the turbine heat rate can recover to 7 980 kJ/kWh, following which degradation will reoccur. This leads to the type of heat rate degradation curve as shown in Figure B2.

**Figure B2 • Typical heat rate degradation curve for a 300 $MW_e$ steam turbine B2**






Source: Courtesy of Li Bo, EDF (China).

This curve provides a useful means to determine if other factors are contributing to the change in heat rate. For example, if, upon inspection, the turbine heat rate is far above the degradation value, this would suggest that other problems beyond normal ageing have occurred. This would then require the flow path to be inspected and perhaps overhauled, with the gap to be adjusted, and a new, improved type of gland seal to be considered. After retrofitting, the HP, intermediate pressure (IP) and LP cylinder efficiencies can be restored to better than 87%, 92% and 89% of the design values respectively.

Other actions that can be considered to optimise the efficiency of turbines include:

- ensuring reasonable overlap of the governing valves' opening for less throttle loss
- avoiding valve passing problems with HP bypass, LP bypass and the inclusion of steam vent/drain valves.

## *Maintain good vacuum in the condenser*

The tightness of the vacuum system is acceptable if the vacuum decreasing speed is less than 270 pascals per minute according to the *Guide of Operation and Maintenance for the Condenser and Vacuum System of Power Plant* (Chinese Code: DL-T 932-2005).

For the closed circuit cooling system, the following conditions indicate that there is performance degradation of the cooling tower:

- when the cooling tower's capacity is less than 95% design water volume
- when the differential between the cooling water temperature at the outlet of the cooling tower and ambient temperature is higher than 8°C at 100% load rate during the summer.

Regular inspection of the cooling tower is required to identify and then address any problems arising.

In China, the water ring vacuum pump is generally used, the performance of which links closely with the temperature of the working fluid. There are measures that can be taken to decrease the working fluid's temperature in order to either maintain or improve the vacuum pump's performance.

The performance of the ball cleaning system for the condenser is an important factor in maintaining an acceptable heat exchange capacity.



For dual backpressure condensers, it is recommended to connect the air extraction lines in parallel.

### *Feedwater heating system*

With the use of an efficient heat exchange unit, the only heat loss is the terminal temperature difference between the incoming makeup water and the blowdown water. Therefore, the aim is to minimise that terminal temperature difference by regular monitoring and remediation measures. For example, tube blockage can occur and this can be addressed by specialised cleaning or by simple replacement.

## Miscellaneous items

There are many other energy-saving options, some of which are touched upon in the main text, that have been implemented in the two power plants that have been studied.

### *Use a boiler feedwater pump*

The turbine-driven pump is a more economical option than an electrical pump and, for a 300 $MW_e$ unit, the net coal consumption rate saving is about 2 gce/kWh.

### *Increase the piping efficiency*

The provision of good insulation for the steam pipes is the main measure for increasing the piping efficiency.

### *Reduce the auxiliary power consumption rate*

There is considerable scope either to reduce the capacity margin of pumps and fans, or to maintain operations at high-efficiency conditions. The main technologies adopted include:

- Variable speed drives (VSDs) for the high voltage motors. This technology is widely used for FD fans, ID fans, condensate pump and the FGD booster fan.
- Dual-speed motors. This technology is widely used in cooling water pumps, FD fans, ID fans and the condensate pump.
- Blade cutting for pumps, which is suitable for the pumps with a large capacity margin.
- Optimisation of the pressure drop in the piping through redesign.
- Introduction of a high frequency power supply for the ESP. This ensures that the voltage fluctuation is small and the corona has high voltage and large current, thus increasing the corona power, which helps counter the low efficiency of charged dust (especially for high specific resistance flue gas dust), so improving the dust removal efficiency of ESP. Power savings can reach 70%.

## *Reduce the air leakage rate for the air preheater*

New sealing technologies can be applied to decrease the air leakage rate from the rotating air preheater to less than 6%, which will help to reduce the auxiliary power consumption of ID fans and FD fans. Degradation will occur, but this is deemed acceptable providing the air leakage rate can be controlled at no higher than 8% within five years.

# Annex C: Detailed project results

Detailed results for Units A3 and B4 are described below.



## Plant A

Plant A was constructed in three stages and comprises six units, two with a capacity of 315 $MW_e$, two more also of 315 $MW_e$, and finally two of 330 $MW_e$, with a total installed capacity of 1 920 $MW_e$. Unit A3, one of the 315 $MW_e$ units, was assessed. It entered commercial operation in May 1997. The boiler, Type SG1025/18.3-M840, was supplied by Shanghai Boiler Works, while the steam turbine, Type N315-16.7/538/538, was supplied by Shanghai Turbine Works.

The coal fired in Unit A3 is obtained from a number of sources. It is generally bituminous coal, although lignite is often added by the supplier. Typical coal composition is shown in Table C1. The total capacity of the coal yard is 531 000 tonnes for the six units, which represented some 22 days stock at full-load operation.

**Table C1 • Average composition of the coal fired in Plant A**

| LHV (MJ/kg) | Ash content (%) | Volatile content (%) | Sulphur content (%) |
|---|---|---|---|
| 19.10 | 30.9 | 35.35 | 1.65 |

Note: Coal composition presented on an as-received basis; data provided by Plant A.

### *Energy-saving projects implemented*

In accordance with Chinese energy-saving policies, several improvements have been made to Unit A3, as summarised in Table C2 and described below:

- Internal leakage in the turbine steam path has been reduced by replacement of the turbine gland seal with improved turbine shaft retractable packing and spring-backed seals. This improvement increases the HP casing efficiency by 2% to 3%, and the IP casing efficiency by 1% to 2%. The coal consumption rate was reduced by 2.9 gce/kWh, which represents an annual $CO_2$ emissions reduction of about 12 500 tonnes.[9]
- Normally, for a 300 $MW_e$ boiler, if the air leakage rate decreases by 12%, the boiler efficiency can be improved by 1%. The sealing system of the air preheater was improved by adopting flexible contact sealing technology, which reduced the air leakage rate from about 10% to 6%. Assuming the benchmark coal consumption rate of 335 gce/kWh, the saving would be around 1.1 gce/kWh, which corresponds to an annual $CO_2$ emissions reduction of about 9 500 tonnes. An associated benefit was a reduction in electric current demand for ID fans, FD fans and primary air fans. Based on annual operation of 6 000 hours, the power saving can be about 5 gigawatt hours per year (GWh/yr). Since the retrofit, the air leakage rate has increased to 7.3%; however, under current power plant practices, it is considered satisfactory if the leakage rate can be maintained below 8% for five years after retrofit.

[9] Based on the following assumptions: utilisation = 5 500 hours per year; standard coal consumption rate = 335 gce/kWh; unit $CO_2$ emissions = 835 kg/kWh; 1 gramme coal-equivalent coal ≡ 2.493 grammes $CO_2$ emission.

- VSDs were applied to the condensate pump motors, which resulted in an auxiliary power saving of around 20% to 25%. For this 315 $MW_e$ unit, the power saving would be about 1.3 GWh/yr, which corresponds to an annual $CO_2$ emissions reduction of about 1 300 tonnes.
- A high frequency power supply was introduced for the ESP, for which the auxiliary power saving was close to 70%. For this 315 $MW_e$ boiler, the power saving would be about 3.6 GWh/yr, which corresponds to an annual $CO_2$ emissions reduction of about 3 600 tonnes.
- Plasma ignition technology was applied to the boiler as a fuel oil saving measure. For a cold unit start-up, from fuel oil consumption of about 50 tonnes, 90% to 100% is now saved. Such an approach can be especially beneficial on units subject to low load operation as well as frequent start-ups and shutdowns.



There is some degree of automatic control installed, namely:

- the combustion control can be put into auto mode, while the air/fuel ratio is maintained partially in auto mode
- the steam soot blowers for the boiler can be operated in either automatic or manual mode.

In addition, two further projects are at the planning stage:

- Application of VSDs to the ID fan motors. As the fan efficiency is already high, however, such an upgrade may not be effective from either a cost or an energy viewpoint. The potential gain will depend to a great extent on the design margin and the operating condition of the unit. VSDs are normally applied to the motors of condensate pumps, FD fans, ID fans and primary fans based on the results of feasibility studies.
- Retrofit of the steam turbine to address various steam leaks and short circuits, realign the flow passage and address any blade problems. The intention would be to decrease the heat rate to 7 864 kJ/kWh. This could save 10 gce/kWh coal, which would be consistent with an annual $CO_2$ emissions reduction of 43 000 tonnes.

**Table C2 • Overview of the performance improvements achieved at Plant A, Unit A3 – Shandong Province**

| Technical modification | Typical reduction in $CO_2$ emissions (t/yr) | Net efficiency increase (percentage points) |
|---|---|---|
| Change the turbine gland seal to an adjustable brandon steam seal | 12 500 | 0.31 |
| Improve the sealing system of the air preheater | 9 500 | 0.24 |
| Apply VSDs to the condensate pump motors | 1 300 | 0.03 |
| Introduce high frequency power supply for ESP | 3 600 | 0.09 |
| Overhaul the flow path of steam turbine (proposed) | 43 000 | 1.08 |

Note: Calculated values may be subject to rounding errors.

## *Overall performance assessment*

These ongoing improvement programmes, together with a proactive operational approach, ensure the unit performs well. This was confirmed following various performance tests that were undertaken in 2010, as shown in Table C3 below.

It should be noted, however, that under typical operating mode the thermal efficiency was nearly 2 percentage points lower than that achieved in the performance test, due to the plant being required to operate at part load.

**Table C3 • Overview of the efficiency data for Plant A, Unit A3**

| | Boiler efficiency (%) | Turbine heat rate (kJ/kWh) | Gross thermal efficiency (%) | Gross coal consumption rate (gce/kWh) | Auxiliary power consumption rate (actual %) | Net thermal efficiency (%) | Net coal consumption rate (gce/kWh) |
|---|---|---|---|---|---|---|---|
| **Design** | 91.6 | 7 921 | 41.2 | 298.3 | 5.48 | 38.9 | 315.6 |
| **Performance test** | 92.1 | 8 099 | 40.5 | 303.6 | 5.48 | 38.3 | 321.2 |
| **Actual** | ~91.6 | ~8 460 | 38.6 | 318.7 | 5.48 | 36.5 | 337.2 |

Notes: Piping efficiency was determined at 99% for all three conditions; the boiler efficiency and turbine heat rate for design and performance test were provided by Plant A (shaded cells in table); 5.48% is the average auxiliary power consumption rate for 2010; for comparison purpose, it is also used to calculate the net efficiency under design condition and performance test condition; the actual net coal consumption rate of 337.21 gce/kWh was the weighted average value for 2010; the other actual values are back-calculated using the 5.48% auxiliary power consumption rate.

## *Scope for further improvements*

The combustion performance was good, with unburned carbon in the fly ash and in the bottom slag just over half the benchmark level of 3% for 300 $MW_e$ units.

The boiler efficiency was also better than the design value, which is a consequence of the decrease in exhaust flue gas heat loss arising from improvements made to the air preheater sealing system.

Similarly, the comprehensive auxiliary power consumption rate was comparatively low, due to the various improvements made, notably:

- the use of a steam turbine-driven boiler feedwater pump
- the introduction of VSDs for the condensate pump motors
- the use of a high frequency power supply for the ESP.

In contrast, the turbine performance was only some 2.2% higher than the design value. This was largely a result of degradation of the turbine cylinders' efficiency, although there was scope for further improvement in the performance of the air preheaters, as well as a need to address any remaining internal leakage in the turbine steam path. It should be possible to address all of these issues during the scheduled retrofit of the turbine.

There should also be scope to address issues arising from the great variation in ambient air temperature between summer (when temperatures reach around 30°C) and winter (when they can be as low as -10°C to -20°C), which results in a much higher exhaust flue gas temperature in the summer. This can be countered with the inclusion of a low temperature economiser, i.e. an additional heat exchanger upstream of the air preheater, to hold the exhaust flue gas temperature at about 130°C all year round.

# Plant B

At the time of writing, the total installed capacity of Plant B was 1 200 MWe, comprising four 300 MWe units, with two additional 600 MWe SC coal-fired units under construction.



Unit B4, the unit under investigation, began commercial operation in December 2000. The boiler, Type HG-1021/18.2-HM5, was supplied by Harbin Boiler Works, while the steam turbine, Type N330/c255-16.7/0.8/537/537, was supplied by Harbin Turbine Works.

The fuel consumed in Unit B4 is lignite, which typically has a low heating value, a high volatile content and high moisture levels (Table C4).

**Table C4 • Coal characteristics for Plant B, Unit B4**

| LHV (MJ/kg) | Ash content (%) | Volatile content (%) | Sulphur content (%) | Total moisture content (%) | Inherent moisture (%) |
|---|---|---|---|---|---|
| 12.57 | 13.48 | 42 | 0.51 | 32.69 | 16.92 |

Note: Coal composition presented on an as-received basis; data provided by Plant B.

The total capacity of the coal yard for the four 300 MWe units was 200 000 tonnes, equivalent to some 24 days coal stock at full-load operation. However, in view of the propensity of lignite to self-combust, the stockpile was generally limited to 100 000 tonnes.

## *Energy-saving projects implemented*

Several energy-saving measures have been implemented in recent years, as set out in Table C5.

**Table C5 • Overview of the performance improvements achieved at Plant B, Unit B4**

| Technical modification | Typical reduction in $CO_2$ emissions (t/yr) | Net efficiency increase (percentage points) |
|---|---|---|
| Overhaul the flow path of the steam turbine | 65 800 | 1.82 |
| Enlarge the capacity of condenser | 5 900 | 0.16 |
| Cut the impeller of the condensate pumps to reduce the capacity margin | 270 | 0.007 |
| Introduce high frequency power supply for ESP | 1 650 | 0.04 |
| Conversion to establish as a co-generation unit | 46 000 | 1.27 |

Note: Calculated values may be subject to rounding errors.

The individual improvements are described below:

- Steam flow path overhaul implemented by replacing the HP inner casing, the HP/IP rotor, the HP/IP/LP blades, blade carriers, and gland seals. This decreased the heat rate to 7 888 kJ/kWh, which resulted in a coal saving of about 16 gce/kWh, which equates to an annual $CO_2$ emissions reduction of some 65 800 tonnes.
- The capacity of the condensers was enlarged, resulting in an annual $CO_2$ saving of 5 900 tonnes. However, it should be noted that this kind of modification is not applicable to all coal-fired power units; a case-specific study is needed to ascertain if it is appropriate to proceed.
- The capacity margin of the condensate pumps was reduced to achieve a power saving of 100 kilowatts (kW) to 120 kW, which resulted in an annual $CO_2$ saving of 270 tonnes. As with the previous modification, this is not applicable to all coal-fired power units and so a case-specific study is needed to ascertain if it is appropriate to proceed.

- A high frequency power supply was integrated into the ESP to reduce auxiliary power consumption. For this nominal 300 $MW_e$ boiler, the power saving was about 1.65 GWh/yr, based on 5 500 hours/year utilisation, which corresponds to an annual $CO_2$ reduction of about 1 650 tonnes.
- The unit was converted to co-generation to achieve better fuel consumption. Based on 170 days heat supply each year with an average capacity of 94 tonnes per hour steam, the annual $CO_2$ reduction was about 196 000 tonnes when compared with use of a separate heat supply boiler, and 46 000 tonnes when compared to the condensing unit.[10]

In addition, combustion control can be put into automatic mode while the air/fuel ratio is partially under automatic control. The steam soot blowers for the boiler can be operated in either automatic or manual mode.

## *Overall performance assessment*

Table C6 provides an overview of the efficiency performance of Unit B4.

**Table C6 • Overview of the efficiency data for Unit B4**

| | Boiler efficiency (%) | Turbine heat rate (kJ/kWh) | Gross thermal efficiency (%) | Gross coal consumption (gce/kWh) | Actual auxiliary power consumption (%) | Net efficiency (%) | Net coal consumption (gce/kWh) |
|---|---|---|---|---|---|---|---|
| Design | 91.5 | 7 876 | 41.4 | 297.0 | 5.52/7.05 | 39.1/38.5 | 314.4/319.6 |
| Performance test | ~91.3 | 7 888 | 41.2 | 298.3 | 5.52/7.05 | 39.0/38.3 | 315.7/320.9 |
| Actual | 91.3 | ~8 144 | 39.9 | 308.0 | 5.52/7.05 | 37.7/37.1 | 326.0/331.4 |

Notes: Piping efficiency was 99% in each case; there was a large difference between the comprehensive auxiliary power consumption rate at 7.05% and the production auxiliary power consumption rate at 5.52%, for reasons that are considered below, and therefore the net efficiency has been calculated for each rate respectively; data in shaded cells were provided by the power plant.

As with Unit A3, under typical operating mode the thermal efficiency was nearly 2 percentage points lower than that achieved in the performance test. Again, this is due in large to the plant being required to operate at part load.

## *Scope for further improvements*

The size distribution of the coal was suitably fine, and the combustion efficiency acceptable, with the unburned carbon in fly ash and in bottom slag at about one-fifth of the benchmark level of 3% for 300 $MW_e$ units.

The boiler efficiency was close to the design value.

The turbine efficiency was very close to the design value, which was the result of a major retrofit undertaken in 2010, shortly before the performance test.

The comprehensive auxiliary power consumption rate was 7.05%, and 5.57% was used for power plant ancillaries, which is quite low as a result of the improvements described above. The comprehensive auxiliary power consumption rate is rather higher, due to the need to provide power for:

[10] = (5 500 hours*300 MW*170 days)/(365 days*6%*1 000 $gCO_2$/kWh).

- construction of supercritical units
- the ash classifying facility
- the heat supply station
- the repair of various coal mills.



Power loss in the main transformer represents about 0.9 percentage points of the auxiliary power consumption rate, which seemed high compared to the benchmark level of closer to 0.3 percentage points. An investigation of the cause of this lay outside the remit of the project.

The exhaust flue gas temperature was about 118°C, and the exhaust flue gas loss was controllable.

From the monthly production data sheets (Annex D), it can be seen that the ID fan power consumption was comparatively high and there would be scope to reduce this.

It was also noted that there was no continuous on-line monitoring of coal quality. As the operations team had no access to coal quality data from the company intranet, there was no scope for application of a management information system to adjust the combustion process according to the quality of coal being fed to the boiler.

# Annex D: Technical performance analysis for the two power plants

Information[11] was provided by the operational personnel at the two power plants for the period January to May 2011, which included month-on-month performance data arising from actual operation rather than from a standardised performance test. This indicates that both plants had been operating at part load and consequently the net efficiencies were lower than their design values.

The net efficiency difference of Unit A3 between the direct and indirect balance calculation methods is constant at 0.3 to 0.4 percentage points. Thus it can be inferred that the actual net efficiency of Unit A3 is 36.2% or higher.

## Performance data for Unit A3, Plant A

| | Average unit load | Auxiliary power consumption rate | Raw coal consumption | LHV of raw coal | Boiler efficiency |
|---|---|---|---|---|---|
| | $MW_e$ | % | tonnes | kJ/kg | % |
| Jan | 242 | 4.92% | 87 388 | 19 273 | 92.1 |
| Feb | 224 | 4.85% | 73 739 | 19 113 | 92.1 |
| Mar | 241 | 4.99% | 31 427 | 19 305 | 92.2 |
| Apr | 239 | 5.06% | 77 199 | 18 944 | 92.2 |
| May | 238 | 5.04% | 87 764 | 18 856 | 92.2 |
| Jan-May | 224 | 4.97% | 357 517 | 19 069 | 92.2 |

Note: kJ/kg = kilojoules per kilogramme.

| | Gross coal consumption rate | | Gross efficiency | | Net coal consumption rate | | Net efficiency | |
|---|---|---|---|---|---|---|---|---|
| | Direct energy balance | Indirect energy balance | Direct energy balance | Indirect energy balance | Direct energy balance | Indirect energy balance | Direct energy balance | Indirect energy balance |
| | gce/kWh | gce/kWh | % | % | gce/kWh | gce/kWh | % | % |
| Jan | 320.0 | 323.3 | 38.4 | 38.0 | 336.5 | 340.0 | 36.5 | 36.2 |
| Feb | 319.3 | 322.8 | 38.5 | 38.1 | 335.6 | 339.2 | 36.6 | 36.3 |
| Mar | 317.3 | 320.8 | 38.8 | 38.3 | 333.9 | 337.7 | 36.8 | 36.4 |
| Apr | 320.1 | 323.4 | 38.4 | 38.0 | 337.2 | 340.6 | 36.5 | 36.1 |
| May | 319.3 | 322.5 | 38.5 | 38.1 | 336.2 | 339.7 | 36.6 | 36.2 |
| Jan-May | 319.5 | 323.0 | 38.5 | 38.1 | 336.2 | 339.9 | 36.6 | 36.2 |

| Boiler | Steam production | Main steam pressure | Main steam temperature | Reheated steam pressure | Reheated steam temperature |
|---|---|---|---|---|---|
| | tonnes | MPa | °C | MPa | °C |
| Jan | 557 545 | 14.59 | 541.7 | 2.84 | 540.6 |
| Feb | 467 778 | 14.10 | 541.1 | 2.62 | 539.5 |
| Mar | 206 285 | 14.16 | 541.1 | 2.59 | 539.2 |
| Apr | 493 702 | 14.29 | 540.6 | 2.77 | 539.9 |
| May | 560 610 | 14.28 | 540.7 | 2.58 | 539.7 |

[11] Data in Annex D came from each individual plant's management information system.

| Boiler | Ambient temperature | Exhaust flue gas temperature | $O_2$ in the exhaust flue gas | Carbon content in the fly ash | BFW temperature | Boiler efficiency |
|---|---|---|---|---|---|---|
| | °C | °C | % | % | °C | % |
| Jan | -2.9 | 121.6 | 3.7 | 1.80 | 266.8 | 92.1 |
| Feb | 2.8 | 122.6 | 3.8 | 1.70 | 261.2 | 92.1 |
| Mar | 8.8 | 123.6 | 3.6 | 1.80 | 258.7 | 92.2 |
| Apr | 16.4 | 128.6 | 3.7 | 1.80 | 261.3 | 92.2 |
| May | 20.9 | 136.9 | 3.5 | 1.87 | 259.9 | 92.2 |

| Turbine | Operating hours | Average unit load | Main steam pressure | Main steam temperature | Circulating cooling water inlet temperature | Exhaust steam temperature |
|---|---|---|---|---|---|---|
| | | MW | MPa | °C | °C | °C |
| Jan | 744 | 242 | 14.40 | 540.6 | 8.9 | 31.9 |
| Feb | 672 | 224 | 13.99 | 540.1 | 12.2 | 32.9 |
| Mar | 271 | 241 | 13.89 | 540.1 | 12.5 | 30.9 |
| Apr | 654 | 239 | 14.09 | 539.2 | 18.8 | 33.5 |
| May | 744 | 238 | 14.11 | 539.9 | 23.2 | 35.2 |

| Turbine | Condenser terminal temperature difference | Condensate sub-cooled temperature | Vacuum | Steam consumption rate |
|---|---|---|---|---|
| | °C | °C | -kPa | kg/kWh |
| Jan | 4.3 | 1.5 | 97.60 | 3.10 |
| Feb | 4.4 | 1.3 | 96.38 | 3.10 |
| Mar | 4.4 | 1.4 | 96.88 | 3.16 |
| Apr | 4.1 | 1.5 | 95.39 | 3.16 |
| May | 4.3 | 1.6 | 94.51 | 3.17 |

Note: kPa = kilopascal.

## Performance data for Unit B4, Plant B

| | Gross generation | Auxiliary power consumption for production | Raw coal consumption | LHV of raw coal | Boiler efficiency |
|---|---|---|---|---|---|
| | GWh | % | tonnes | kJ/kg | % |
| Jan | 158.60 | 5.36 | 116 859 | 12 415 | 90.42 |
| Feb | 135.67 | 5.79 | 98 400 | 12 412 | 91.09 |
| Mar | 78.94 | 5.80 | 56 700 | 12 578 | 91.18 |
| Apr | 72.05 | 5.61 | 52 170 | 12 655 | 91.33 |
| Jan-Apr | 445.30 | 5.61 | 324 129 | 12 481 | 90.90 |

Note: GWh = gigawatt hour.

| | Gross coal consumption rate | | Gross efficiency | | Net coal consumption rate | | Net efficiency | |
|---|---|---|---|---|---|---|---|---|
| | Direct energy balance | Indirect energy balance | Direct energy balance | Indirect energy balance | Direct energy balance | Indirect energy balance | Direct energy balance | Indirect energy balance |
| | gce/kWh | gce/kWh | % | % | gce/kWh | gce/kWh | % | % |
| Jan | 312.4 | 313.9 | 39.4 | 39.2 | 330.1 | 331.7 | 37.3 | 37.1 |
| Feb | 307.5 | 311.7 | 40.0 | 39.5 | 326.4 | 330.8 | 37.7 | 37.2 |
| Mar | 308.6 | 309.1 | 39.8 | 39.8 | 327.7 | 328.1 | 37.5 | 37.5 |
| Apr | 313.0 | 309.1 | 39.3 | 39.8 | 331.6 | 327.4 | 37.1 | 37.6 |
| Jan-Apr | 310.4 | 311.6 | 39.6 | 39.5 | 328.8 | 330.1 | 37.4 | 37.3 |

Note: gce/kWh = grammes coal-equivalent per kilowatt hour.

| Boiler | Air leakage rate | | | Exhaust flue gas temperature |
|---|---|---|---|---|
| | Air preheater | Boiler proper | Milling system | |
| | % | % | % | °C |
| Jan | 8.05 | 7.10 | 23.41 | 113.3 |
| Feb | 9.32 | 7.10 | 24.22 | 113.8 |
| Mar | 7.22 | 7.85 | 26.01 | 113.6 |
| Apr | 8.25 | 7.85 | 23.81 | 118.5 |
| Jan-Apr | 8.32 | 7.35 | 24.20 | 114.35 |

| Boiler | Ambient air temperature | $O_2$ content in exhaust flue gas | Carbon content in the fly ash | Carbon content in the bottom ash | Boiler efficiency |
|---|---|---|---|---|---|
| | °C | % | % | % | % |
| Jan | -15.00 | 2.90 | 0.62 | 8.02 | 90.42 |
| Feb | -6.30 | 2.75 | 0.47 | 6.83 | 91.09 |
| Mar | -2.40 | 2.91 | 0.55 | 7.43 | 91.18 |
| Apr | 10.50 | 3.97 | 0.64 | 6.36 | 91.33 |
| Jan-Apr | -5.99 | 3.03 | 0.57 | 7.28 | 90.90 |

| Turbine | Gross generation | Average unit load | Main steam pressure | Main steam temperature | Reheated steam pressure | Reheated steam temperature |
|---|---|---|---|---|---|---|
| | GWh | MW | MPa | °C | MPa | °C |
| Jan | 158.6 | 213.2 | 16.16 | 539.7 | 2.10 | 538.9 |
| Feb | 135.7 | 201.9 | 16.38 | 539.4 | 2.58 | 537.7 |
| Mar | 78.9 | 207.1 | 15.50 | 539.9 | 2.00 | 535.5 |
| Apr | 72.1 | 197.1 | 14.78 | 539.5 | 1.92 | 535.4 |
| Jan-Apr | 445.3 | 205.9 | 15.65 | 539.7 | 2.07 | 537.3 |

| Turbine | Circulating cooling water inlet temperature | Circulating cooling water outlet temperature | Condensate sub-cooled temperature | Condenser terminal temperature difference | Vacuum | Steam consumption rate |
|---|---|---|---|---|---|---|
| | °C | °C | °C | °C | -kPa | kg/kWh |
| Jan | 10.8 | 24.0 | 0.9 | 5.20 | 97.10 | 3.08 |
| Feb | 10.7 | 22.5 | 0.7 | 6.30 | 96.58 | 3.24 |
| Mar | 9.8 | 21.8 | 0.9 | 8.00 | 95.86 | 2.84 |
| Apr | 18.3 | 27.1 | 0.8 | 4.90 | 94.14 | 2.90 |
| Jan-Apr | 11.8 | 23.65 | 0.8 | 5.98 | 96.24 | 3.06 |

# Annex E: Data from a complementary study

**Table E1 • Results from APEC study**

| Improvement | | Net efficiency gain (percentage points) |
|---|---|---|
| **Combustion system**: | Pulveriser and feeder upgrades | 0.3 |
| | Air preheater repair or upgrade | 0.25 |
| | Soot blower improvements | 0.35 |
| | Excess air instrumentation and control (I&C) | 0.2 |
| **Steam cycle**: | Feedwater heater repairs | 0.4 |
| | Heat transfer tube upgrades | 0.6 |
| | Steam turbine blades | 0.5 |
| | Cycle isolation | 0.5 |
| | Condenser repairs | 0.4 |
| **Operations and maintenance (O&M)**: | O&M training | Included in combustion and steam cycle gains. Efficient operation realised over the long term. |
| | Computerised management and reliability-centred maintenance systems | |
| | Distributed control systems | |
| **Combined total** | | **3.5** |

Source: APEC (2005), Costs and Effectiveness of Upgrading and Refurbishing Older Coal-Fired Plants in Developing APEC Economies, APEC Energy Working Group Project EWG 04/2003T, APEC, Singapore.

The information provided in the APEC report (2005) includes detailed technical equipment and systems improvement descriptions, prioritisation tables and case studies that show how plant equipment upgrading and refurbishment projects can be justified. This information is not at the design level of detail, but should be sufficient to facilitate communications between government, plant operations, management, plant operators and others involved in upgrading and refurbishment projects. References are provided for additional design information. The focus is on pulverised coal-fired plants, but portions of the information and methodology provided are also applicable to other types of plant.

# References

APEC (Asia-Pacific Economic Cooperation) (2005), Costs and Effectiveness of Upgrading and Refurbishing Older Coal Fired Plants in Developing APEC Economies, APEC Energy Working Group Project EWG 04/2003T, APEC, Singapore.

CEC (China Electricity Council) (2013), China Electricity Industry Annual Development Report, CEC, Beijing.

CIAB (Coal Industry Advisory Board) (2010), Power Generation from Coal: Measuring and Reporting Efficiency Performance and CO2 Emissions, International Energy Agency CIAB, Paris, www.iea.org/ciab/papers/power_generation_from_coal.pdf.

European Commission (2005), International Cooperation to Improve Efficiency and Reduce Environmental Impact for Fossil Fuel Fired Power Plants within China, final report of a collaborative EU-China project undertaken as Contract NNE5/2001/552, European Commission, Brussels.

IEA (2013), Medium-Term Coal Market Report 2013, OECD/IEA, Paris.

IEA (2012), Energy Technology Perspectives 2012, Organisation for Economic Co-operation and Development (OECD)/IEA, Paris.

IEA (2014a), Tracking Clean Energy Progress Report 2014, OECD/IEA, Paris.

IEA (2014b), Energy Technology Perspectives 2014, OECD/IEA, Paris.

Mao, J. and W. Feng (2012), "Ways to Further Improve Efficiency for Ultra-supercritical Coal-fired Power Plants in China", presented at the IEA CCC Workshop on Advanced USC Coal-fired Power Plants, Vienna, Austria (19-20 September).

Mao, J. (2011), "Ultra-Supercritical Technology – the Best Practical and Economic Way to Reduce CO2 Emissions from Coal Fired Power Plants", presented at the 7th International Symposium on Coal Combustion, Harbin, China (18-20 July).

Mi, J. (2010), "Upon Power Efficiency in China", International Workshop on Industrial Energy Efficiency, New Delhi, India (27-28 January), http://beeindia.in/seminars/document/2010/Mi%20Jianhua.pdf.

Minchener, A. (2010), Developments in China's Coal-Fired Power Sector, Report CCC 163, IEA CCC, London (January).

NDRC (National Development and Reform Commission) (2007a), Proposal to State Council for Accelerating Decommission of Inefficient Small Size Generating Units, NDRC, Beijing.

NDRC (2007b), Regulation on Energy Conservation Power Generation Dispatching (try out), jointly issued by NDRC, SEPA, SERC and Office of National Leading Group on Energy, Beijing.

NEA (National Energy Administration) (2013), 12th Five-Year Plan for Energy, State Council, Beijing.

NETL (National Energy Technology Laboratory) (2008), Reducing CO2 Emissions by Improving the Efficiency of the Existing Coal-Fired Power Plant Fleet, DOE/NETL-2008/1329, NETL, Pittsburgh, PA, www.netl.doe.gov/energy-analyses/pubs/CFPP%20Efficiency-FINAL.pdf.

PlanetArk (2007), China to Require Swap of Old Coal Plants for New, 1 Feb, www.planetark.com/dailynewsstory.cfm/newsid/40107/newsDate/1-Feb-2007/story.htm.

RAP (Regulatory Assistance Project) (2008), China's Power Sector: a Backgrounder for International Regulators and Policy Advisors, www.raponline.org/document/download/id/13.

Schilling, H. (1993), "Improving the Efficiency of Pulverised Coal Fired Power Generating Plant", in VGB KraftwerksTechnik (English edition), Vol. 73(8), pp. 564-576.

VGB PowerTech (2012), Facts and Figures: Electricity Generation 2012/2013, VGB PowerTech, Essen, www.vgb.org/en/data_powergeneration.html?dfid=55643.

WCA (World Coal Association) website (2014), How is Coal Converted to Electricity? WCA, London, www.worldcoal.org/coal/uses-of-coal/coal-electricity/ (accessed 5 March 2014).

Zhao, Z. (2004), "CO2 Reductions through Efficiency Improvement to Existing Coal-Fired Power Plants and Deployment of Supercritical Units in China", presented at APEC workshop, Queensland, Australia, 16 February, www.egcfe.ewg.apec.org/publications/proceedings/EGCFE/CO2emissions_Australia_2004/presentations/zongrang.pdf.

Zhu, F., S. Wang and H. Li (2010), The Current Status and Prospect of Air Pollution Control for Power Sector in China, http://apiperu.com.pe/argentina/trabajos/ECC_241_ZHU_Fa_hua.pdf.

# Acronyms, abbreviations and units of measure

## Acronyms and abbreviations



| | |
|---|---|
| APEC | Asia-Pacific Economic Cooperation |
| CCS | carbon capture and storage |
| CEC | China Electricity Council |
| CFBC | circulating fluidised bed combustion |
| $CO_2$ | carbon dioxide |
| CSP | concentrated solar power |
| DRC | Development and Reform Commission |
| ESP | electrostatic precipitator |
| FD | forced draft |
| FGD | flue gas desulphurisation |
| GHG | greenhouse gas |
| HHV | higher heating value |
| HP | high pressure |
| I&C | instrumentation and control |
| ID | induced draft |
| IEA | International Energy Agency |
| IP | intermediate pressure |
| LHV | lower heating value |
| LP | low pressure |
| LSS | Large Substitutes for Small |
| MEP | Ministry for Environmental Protection |
| NDRC | National Development and Reform Commission |
| NEA | National Energy Administration |
| NETL | National Energy Technology Laboratory |
| NOX | nitrogen oxides |
| O&M | operations and maintenance |
| OECD | Organisation for Economic Co-operation and Development |
| PV | photovoltaic |
| R&D | research and development |
| SC | supercritical |
| SCR | selective catalytic reduction |
| $SO_2$ | sulphur dioxide |
| TIMES | The Integrated MARKAL-EFOM System |
| USC | ultra-supercritical |
| US DOE | United States Department of Energy |
| VSD | variable speed drive |
| WCA | World Coal Association |

## Units of measure

| | |
|---|---|
| gce/kWh | grammes coal-equivalent per kilowatt hour |
| $gCO_2$/kWh | grammes of carbon dioxide per kilowatt hour |
| Gt | gigatonne |
| $GW_e$ | gigawatt electrical capacity |
| GWh | gigawatt hour |

| | |
|---|---|
| GWh/yr | gigawatt hours per year |
| kcal/kg | calories per kilogramme |
| kg/kWh | kilogrammes per kilowatt hour |
| kgce/kWh | kilogrammes coal-equivalent per kilowatt hour |
| kJ/kg | kilojoules per kilogramme |
| kJ/kWh | kilojoules per kilowatt hour |
| kPa | kilopascal |
| kW | kilowatt |
| kWh | kilowatt hour |
| MJ/kg | megajoules per kilogramme |
| MPa | megapascal |
| Mt | million tonnes |
| MW | megawatt |
| MWe | megawatt electrical capacity |
| t/yr | tonnes per year |
| TWh | terawatt hour |
| °C | degrees centigrade |

IEA Publications
9, rue de la Fédération, 75739 Paris cedex 15

Printed in France by IEA, May 2014
Cover design: IEA. Photo credits: © Photodisc and © Corbis.

# *Emissions Reduction through Upgrade of Coal-Fired Power Plants*

## Learning from Chinese Experience

Coal is the principal fuel for the global generation of electrical power. It is the leading source of power generation in OECD countries and the dominant fuel source behind economic growth in non-OECD countries. However, while coal provides over 40% of the world's electricity, it is responsible for more than 70% of the $CO_2$ arising from electricity generation. Local air pollution arising from coal-fired electricity generation has also come under close public scrutiny in the communities and urban areas where plants are located.

Carbon capture and storage is not yet cost-effective for large-scale application. In the meantime, while new plants deploy high-efficiency, low-emissions technologies, ensuring that the existing fleet of coal-fired plants operate at the highest possible efficiency can lead to reduced $CO_2$ emissions, lower fuel consumption, improved air quality and decreased water demand.

This report examines the potential for improvement in the performance of existing coal-fired plants. Two operating units were selected to identify measures that would improve their net efficiency. Each unit was investigated to explore the means to improve the efficiencies of its boiler and its turbine as well as to reduce the auxiliary energy consumption of the unit as a whole. The results demonstrate the enormous potential to increase efficiency, with each percentage point increase capable of reducing $CO_2$ emissions by many millions of tonnes over a unit's operational lifetime.

China is undertaking a major national energy efficiency improvement programme, which includes improving the thermal efficiency and environmental performance of its existing coal-fired power plants. China's experiences showcase the benefits of improving coal-fired power plant efficiency for a global audience.