CO_2 reductions from CCTs and CO_2 capture

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Abstract

The efficiency of a fossil-fired plant has a direct effect on its CO_2 emissions. Efficiencies of coal-fired power plants vary considerably around the world, and there is a potential for major CO_2 emissions savings by upgrading or replacements. This report provides estimates of the potential emissions savings through efficiency improvements and plant replacements using modern systems (clean coal technologies), for six coal-consuming countries. These are China, India, South Africa (non-OECD), the USA, Australia and the UK (OECD). In the future, CO_2 capture and storage is likely to provide an economic means to reduce emissions further, and savings from this are also estimated.

Acronyms and abbreviations

A-USC	A-USC advanced ultra-supercritical (with 700ºC+ turbines)
BHEL	Bharat Heavy Electricals Ltd
CCS	CO_2 capture and storage or carbon capture and storage
CCTs	clean coal technologies
CEA	Central Electricity Authority (India)
CFBC	circulating fluidised bed combustion
CO_2	carbon dioxide
ECPG	Energy Conservation Power Generation (scheduling programme on trials in China)
EJ	exajoules
EPA	Environmental Protection Agency (USA)
EU	European Union
FGD	flue gas desulphurisation
Gt	gigatonne
GW	gigawatts
HHV	higher heating value
IEA	International Energy Agency
IEA CCC	IEA Clean Coal Centre
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt hours
LCPD	Large Combustion Plant Directive (EU)
LHV	lower heating value
MPa	megapascals
MW	megawatts
OECD	Organisation for Economic Cooperation and Development
PCC	pulverised coal combustion
PLF	plant load factor (India)
R & M	renovation and modernisation
SC	supercritical
TJ	terajoules
TWh	terawatt hours
USC	ultra-supercritical
US DOE	US Department of Energy
WEO	World Energy Outlook (IEA)

Contents

1 Introduction

Coal-fired electricity plants provide about 40% of world power and give rise to more than a quarter of world energy-related CO_2 emissions. Although there are other influencing factors, the emissions of CO_2 from these plants principally depend on the extent to which they are used, the fuels burned, and their thermal efficiencies. This work focuses on the latter: efficiencies vary considerably around the world, and there is a potential for major CO_2 emissions savings in both non-OECD and OECD countries. In this report we provide estimates of the potential emissions savings through efficiency improvement measures and replacement with new plants of higher efficiency (clean coal technologies), for six coal-consuming countries. In the future, CO_2 capture and storage is likely to provide an economic means to reduce emissions further, and savings from this are also examined.

In most industrialised countries with coal-fired steam plant of about 30 years age and more, turbogenerator upgrades to return them to original performance or even better have been in progress for a few years and are ongoing. Such works generally involve installing modern profile blading and new seals. This is almost always a worthwhile investment because it is cost-saving, from a resultant reduced fuel consumption.

Significant further efficiency improvements require large-scale refurbishment works to convert subcritical systems to much higher (ultra-supercritical) steam conditions. To limit the cost, this would involve using as much as possible of the existing common services such as cooling water supply, coal supply equipment and limestone and ash handling. The cost would vary greatly from site to site, although it lies broadly in the range 30–60% of a new USC plant cost.

Introduction of CO_2 capture would give most emissions saving benefit, but retrofitting it would only be appropriate to long-life plant. It is of course likely to become the principal solution for new coal-fired plants in the longer term. In this work, we have attempted a bottom-up approach to estimating the emissions reductions, that is from the level of classes of power plants within a selection of major coal consuming countries.

The remainder of this report is organised as follows. Chapter 2 describes the methodology for the work and the sources and types of input data used. Chapters 3 to 8 summarise the current situation for coal-fired power generation in each of six countries examined, then describe the results of the assessments. Chapter 9 is a summary and conclusions.

2 Methodology

2.1 Overview

The countries, from both the OECD and non-OECD areas, were selected to include a sizable fraction of world coal-fired power capacity (over 70%) to enable the scale of CO_2 reductions to be gauged. Different improvement strategies are applicable in different countries because of differing plant population structures, coal qualities, physical location factors, and government policies. The countries were China, India, South Africa (non-OECD), the USA, Australia and the UK (OECD). The most appropriate approaches to improving CO_2 emissions were then considered from among the following: upgrading existing subcritical units by different technical options, replacements with supercritical (SC) or ultra-supercritical (USC) pulverised coal fired systems, and replacements with integrated gasification combined cycle (IGCC) systems. Information on the units in the countries was collected, the plants categorised into groups, then efficiencies assigned to each group. The generation and CO_2 emissions were calculated first for a baseline situation, then for different scenarios based on appropriate improvement assumptions. The primary baseline year was 2015, so plants under construction now, or almost certain to be started shortly, could be included in the evaluations.

The situation in 2030 was examined using two baselines. In the first 2030 baseline approach, the estimates are based on the remaining plant only, after a rundown in capacity from the 2015 level due to retirements, with scenarios based on this including improvement options from replacement with A-USC or advanced IGCC plants and also addition of CCS. For the other 2030 baseline, plant replacements and new plants were assumed to be added between 2015 and 2030 to meet an estimated or assumed total capacity growth rate, then different scenarios examined around that. The effect of CO_2 capture was assessed from 2030 baselines only.

2.2 Tabulation of plant tranches

Basic input information on existing plants and those currently under construction (output, first date of operation, fuel type) was taken from the IEA Clean Coal Centre's Coal Power database. Additional information from various sources, for example on new plants, was then incorporated. Inevitably, some of the information on status (for example, under construction, as opposed to planned) conflicted with information from Coal Power and so judgements had to be made regarding inclusion. Information on new plant constructions is fluid, giving rise to changing data and considerable uncertainty for some countries. Capacity estimation was frozen in mid-January, 2012.

Classifying the plants into tranches was required for each country. Various principles were investigated to identify the best way to classify the plants, so that it would be most straightforward to estimate the efficiencies of the groups. It was decided to separate the hard (black) coal plants from the lignite (brown coal) plants, then to separate the supercritical and ultra-supercritical plants from the subcritical plants within the two categories. Subbituminous coals were regarded as black coals. Integrated gasification combined cycle (IGCC) plants were listed separately, where applicable (there are few of them currently). The total electrical capacity of each of the basic main groups was then tabulated according to date of first operation, within five-year intervals. This allowed a clear picture of the working life of each tranche, by applying assumptions on economic life.

2.3 Estimation of efficiencies of the tranches

Indicative efficiencies were estimated for the tranches of plants grouped by commissioning date to allow a picture of how the efficiency of the country stock of coal-fired power plant units might be

Table 1 Example country datasheet (using the Indian data)

Commissioning date	% efficiency LHV	MWe	% efficiency LHV	MWe
	Hard coal		Lignite	
SC and USC				
Up to 1970				
1971-1975				
1976-1980				
1981-1985				
1986-1990				
1991-1995				
1996-2000				
2001-2005				
2006-2010				
2011-2015	41	48380	40	1320
TOTALS		**48380**		**1320**
SUBCRITICAL				
Up to 1970 + ⩽100 MW (no date)	24	3850	22	792
1971-1975	25	2663	24	280
1976-1980	28	5530	24	540
1981-1985	30	9985	29	320
1986-1990	31	15115	29	810
1991-1995	31	10188	30	1330
1996-2000	33	7845	25	380
2001-2005	34	8817	30	795
2006-2010	35	27337	29	1335
2011-2015	36	42060		
TOTALS		**133390**		**6582**
IGCC				
1996-2000				
2001-2005				
2006-2010				
2011-2015				
TOTALS				

Efficiency basis: all LHV, gross, estimated annual average
Situation in 2015; based on operating or believed under construction, less those expected to close before end 2015

expected to develop over time so that it could be used as the foundation of the baseline. The efficiencies of all the groups were estimated using in-house expertise and experience, together with external information. Older plant age tends to be associated with less advanced design and lower steam parameters, as well as smaller unit size, so grouping by commissioning date is actually logical from the technology point of view. Table 1 shows an example of a datasheet. The efficiencies and capacities are on a lower heating value (LHV), gross generation, basis, because the Coal Power database uses this measure of capacity and it facilitated checks with IEA data on generation, which is tabulated on a gross basis.

Operating efficiencies of power plants are not generally made available by plant owners, and their bases can be uncertain even where they are available. A piece of work carried out by the Clean Coal Centre a few years ago for the IEA Secretariat (Barnes and others, 2007) provided first estimates for approximately 1500 units where plant steam parameters and other data were known. Currently, about 60% of the records in Coal Power have steam parameters, and these, together with plant size and age, nature of systems installed and location, were used in the consideration of efficiency assignments for all the plant tranches. The process used here in estimating the efficiencies did not attach fixed values to the existence of particular features, although plants operating in different climatic conditions, or consuming coals containing much higher ash contents, were assigned efficiency estimates that took such factors into account. A summary of such influences is shown in Table 2. Some of the assumptions for new plants were taken from WEO 2011 draft assumptions. Literature reports of operating efficiencies were also used as input.

Efficiency estimation will always have potential for errors. However, a rigid, automated approach to calculating the efficiencies of all the plants was not possible because of lack of data or precise knowledge of the basis for data. If adopted, it would have needed a subsequent close survey of the results in a process analogous to that adopted here. In other words, estimating indicative efficiencies for groups of plants is a more realistic and practical objective for a task of this nature than deriving them for the individual plants from their parameters. There is considered to be an uncertainty in the efficiencies assigned of up to plus or minus two percentage points (about 5% of value), but usually less than this. However, differences in emissions, from introducing assumed changes, will be subject to less uncertainty. A check was made against published information calculated from IEA data on national average efficiencies of the coal plants as a whole where it was possible for some of the countries as of certain known dates (Graus and others, 2007, 2008), by calculating the overall average efficiencies for the individual countries. The data were then adjusted where necessary in order to reconcile them with these values. Again, some uncertainty inevitably remains, because capacity utilisations vary between plants, and this will influence the resultant country fleet's average efficiency, but the comparison provided reassurance that the methodology used was acceptable and that the efficiency values were sufficiently close.

Finally, it is worth noting that when the published generation and fuel usage have been used in studies of generation efficiencies for whole systems of fossil-fired plants, the results generally point to rather lower performance than appears to be commonly believed, even where the plants are fairly recent (as shown in the work of Graus and others, 2007 and 2008, for example). This has implications for the assumptions to be made for replacement plants: operating efficiencies over a whole year have to be assumed to be significantly below design data.

Table 2 Some factors influencing efficiency estimates, with approximate ranges

Factor	High ash coals (>20%)	Warm/hot climate	Lignite
Efficiency effect, % points	–3	–1 to –2	–1

2.4 Calculation of generation and CO_2 emissions

The individual country datasheets referred to in Section 2.3 were designed to fit into larger spreadsheet models for the calculation of system CO_2 emissions. Other outputs were system generation, specific emissions and efficiency. The structure of the overall spreadsheet models is shown in Figure 1. As indicated earlier in this chapter, subbituminous coals were treated as bituminous for the purpose of this analysis, so the same emission factor was used for both (94.6 tCO_2/TJ). The IPCC emission factor for subbituminous coal is actually 1.5% higher, but this would lead to minor effects on the estimates of CO_2 emissions and savings in comparison with the potential uncertainties from predictions of future plant capacities, capacity factors and efficiencies.

The model was designed to have means to apply input assumptions regarding the utilisation of the plant tranches and the rate of decrease (if any) in utilisation as units aged. Using these, the capacity factors of the tranches of plants were adjusted for each country until a satisfactory agreement with published information on electricity generated in recent years (for example, from IEA publications) was achieved. Details of these calibrations are given in the report chapters on the individual countries. The age at which a unit was assumed to be retired could also be input. Depending on the fleet age structure in the particular country, this can have a minor or a major effect on capacity surviving to 2030, and hence on calculated generation and emissions from those plants by that date. Another assumption that could be input was the change in efficiency into the future as equipment aged: this was set at 1% of value per five years in all cases.

Among the external data sources used to calibrate the model for some of the countries were the published national greenhouse gas inventories, containing generation, fuel use and CO_2 emissions. Thus, published generation, CO_2 emissions and fuel inputs were used where possible to ensure that the model was giving realistic values, and so suitable for predicting the emissions changes for the selected improvement options.

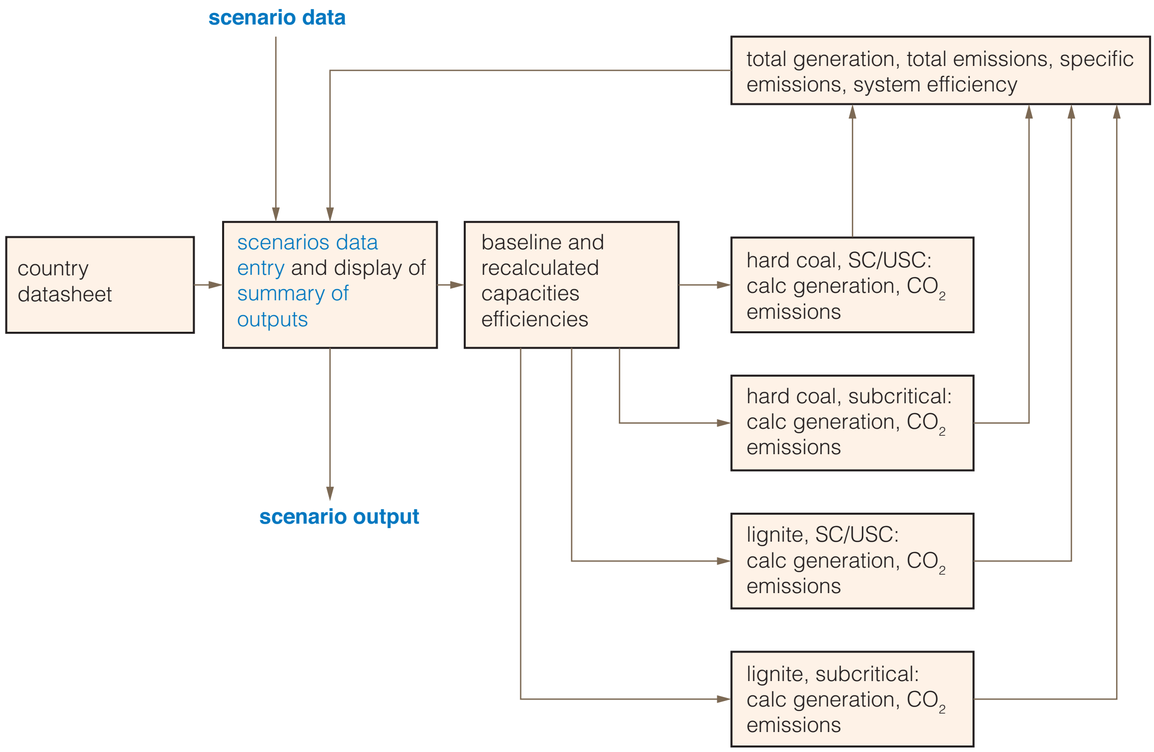

Figure 1 Structure of spreadsheet model

In estimating the CO_2 emission effects as a result of the deployments, parameters that could be varied included plant life, extent of upgrade (percentage points), proportion to be closed, additional or replacement capacity with its efficiency and whether or not including CCS, together with associated timings. Note that the additional auxiliary power demands of CO_2 capture and storage do not appear in the tables in this report, as the efficiency and power are expressed on a gross generated basis. The impact on CO_2 emissions of additional generation to compensate for the extra power needs of the system is not assessed in this report.

For the 2030 scenarios, the model also had the facility to set a desired capacity growth rate, allowing for retirements, so that it was possible to achieve a target capacity in that year.

3 China

3.1 Current situation

China has by far the world's largest fleet of coal-fired power stations (currently over 760 GW). There is an increasing proportion of supercritical and ultra-supercritical units of 600 MW and higher unit size. These have greatly improved efficiency compared with the older, smaller subcritical capacity. Table 3 shows the plants for China, categorised by dates of first operation, together with the efficiencies assigned to the categories in this work. As in the rest of this report, plants that have already closed or are due to close before 2015 are excluded. Those assumed closing in the next few years are all the 100 MW and smaller units, although many units up to 200 MW could also close within the next ten years. Ultimately only 300 MW and larger units are expected to remain, except for cogeneration plants and circulating fluidised bed combustion (CFBC) units firing low grade waste coals (Minchener, 2010). There is also rapid deployment of CFBC units of 300 MW to burn both low grade and high grade coals, and the first of a larger, supercritical design, is under construction.

The capacity data has come from the Coal Power dataset, with extra information from Feng and Yu (2012) and Minchener (2010, 2011) on the recent supercritical and USC build, as well as on the very substantial recent rise in deployment and ordering of CFBC systems. The majority of future coal-fired power plants in China are expected to be 600 MW and 1000 MW SC and USC units, and Chinese manufacturers are now developing 1320 MW USC and 600 MW SC CFBC units.

The information in Table 3 illustrates the rapid modernisation of the Chinese coal-fired fleet through the introduction of supercritical and ultrasupercritical units in the last decade, together with a reduced deployment of subcritical systems apart from CFBC. In Section 3.3 it is shown that this, together with the closure of small plants, means that China's coal-fired power sector has probably already reached the average performance in the OECD area.

The estimated coal-fired capacity in 2010 for China was consistent with information provided by Chen and Liu (2011), which was 962 GW for total capacity by that date, over 70% of which was thermal. It was also consistent with an article in Power Engineering International (2011), which cites 707 GW for thermal capacity at the end of 2010. The total here entered for coal for 2015 is 986 GW, including existing capacity, based on recent information from Feng and Yu (2012). The supercritical and USC build to 2015 was adjusted to achieve the 986 GW total coal capacity. Chen and Liu cite an approximate future coal capacity growth of 75% between 2010 and 2030 (Chen and Liu, 2011). The model showed this to be equivalent to a 2.74%/y growth rate in capacity, and this rate was applied starting from the 986 GW in 2015. It resulted in an estimated capacity in 2030 of 1479 GW.

3.2 Model calibration

Although the model is basically for calculating the *technical* CO_2 savings that could be achieved by different means, suitably representative values for plant capacity factors are needed for the calculation to be meaningful. IEA Electricity Information (IEA, 2010) gives gross generation from hard coal of 2708 TWh in 2008. The thermal capacity that year was 601 GW, and the proportion of thermal capacity that was coal-fired was over 94% at the end of 2007 (Minchener, 2010). Assuming the same proportion in 2008, the coal capacity then was 565 GW. The estimated system capacity factor on this basis was around 55%.

Another check of the capacity factor was made as follows. Recent data from IEA shows that generation from coal in China had grown to 2913 TWh in 2009 (IEA, 2011a). Applying the growth rate between 2008 and 2009 to the following 12-month period gives a generation of about 3118 TWh

Table 3 Chinese coal plants data				
Commissioning date	% efficiency LHV	MWe	% efficiency LHV	MWe
	Hard coal		Lignite	
SC and USC				
Up to 1970				
1971-1975				
1976-1980				
1981-1985				
1986-1990				
1991-1995	40	1700		
1996-2000	40	3140	40	1000
2001-2005	42	10250		
2006-2010	43	115930	42	2520
2011-2015	44	25360		
2007-2015	44	346838		
TOTALS		**503218**		**3520**
SUBCRITICAL				
no date >100 MWe	34	6130		
Up to 1970				
1971-1975 >100 MWe	33	650		
1976-1980 >100 MWe	33	4745	36	300
1981-1985 >100 MWe	34	10595	38	600
1986-1990 >100 MWe	35	29017	36	1200
1991-1995 >100 MWe	36	39560	36	300
1996-2000 >100 MWe	35	62871	37	800
2001-2005 >100 MWe	35	100888	35	1400
2006-2010 >100 MWe	36	92105	35	1000
2011-2015 + no date >100 MWe	37	19560		
Other >100 MWe CFBC (from Minchener, 2010)	35	33915		
Other CFBC ≤100 MW (from Minchener, 2010)	30	73376		
TOTALS		**473412**		**5600**
IGCC				
2011-2015	43	250		
TOTALS		**250**		
Efficiency basis: all LHV, gross, estimated annual average Situation in 2015; based on operating or believed under construction, less those expected to close before end 2015				

for 2010. Applying a plant capacity factor of 55% in the model gave total power generation of 2862 TWh in 2010. However, as discussed above, the model considers only those plants expected to be active in 2015, and so units of less than 100 MW capacity are not in these estimates for 2010. Although, by 2015, most of these plants should have been closed, in 2010 the capacity of these small units was expected to be still about 60 GW, having dropped from 114 GW in 2006 (based on information within Minchener, 2010). The generation for 2010 with 60 GW temporarily added to the capacity in the model was therefore determined: this was 3151 TWh, showing that the 55% capacity factor assumption was sufficiently realistic for inputting to the model. Given the rapid deployment of new capacity in China and the uncertainties in the estimates of generation, the capacity factor may differ from this value potentially by up to a few percentage points, but the combined effect of estimated capacity and estimated utilisation should be sufficiently close for realistic estimates of generation and emissions in the following sections.

3.3 Baseline CO_2 emissions (2015)

The previous section described the adjustment of the system capacity factor to calibrate the model against other data on power production. Assuming a distribution of capacity factors, with older plants having lower values is reasonable for many countries, but this is not realistic for China at present. For example, even setting the value at a conservative 80% for a new plant group, with five percentage points decline each succeeding five years, still gave a system capacity factor of 74% in 2010 and 72% in 2015. Increasing the rate of decrease to as much as 10% each five years was far from sufficient to reduce the system capacity factor to 55% in 2010. The reason is that a distribution of capacity factors does not reflect the manner in which the system is currently operating in China. As has been described by Minchener (2010), it has been normal for all units to bear the grid load equally, regardless of their efficiency. Consequently, the more recent plants are running at capacity factors well below what would be expected for new units elsewhere, while old, inefficient units are being used excessively instead of being closed. There have been trials of a new system – the Energy Conservation Power Generation (ECPG) scheduling programme – to correct this situation, further encourage closure of old plants, and so obtain the full benefits of the fleet modernisation. Reform of the pricing mechanism would be needed also. However, it is unclear when nationwide introduction of such measures will actually occur (Minchener, 2010).

Because of the above, the capacity factor used for all plants was set to the same value of 55%. The model's predicted CO_2 emissions based on this are shown in Table 4. The large capacity will result in 4.2 Gt being emitted in 2015. However, the fleet specific emission of CO_2 of 882 g/kWh (gross) is relatively low. This is because of the good average efficiency expected by 2015 due to the large increase in supercritical and USC capacity. The predicted average fleet efficiency is 38.6% LHV, gross basis. For comparison, using data from IEA (2010), the average efficiency of power generation from coal-fired electricity plants in the OECD area in 2008 for coal plus lignite was 37.5% LHV, gross. This was based on 2008 data from that reference of 3,010,685 GWh from 28,775,273 TJ of hard coal and patent fuel, plus 484,616 GWh from 4,817,094 TJ of lignite and brown coals. Thus China's coal-fired power sector has probably reached the performance of the OECD area.

3.4 Scenarios from 2015 baseline

It is clear from the discussion earlier that China is already committed to deploying CCTs to replace the more inefficient of its existing capacity. For this study, we look at what benefits in CO_2 emissions reductions could come from some further measures.

An illustration of the effect of replacing overnight all of the subcritical units (including CBFC) by USC units of 44% LHV, gross, annual average efficiency (and one percentage point less for lignite) is shown in Table 4. Emissions would drop by about 500 Mt/y if the same amount of power was

Table 4 CO2 emissions, generation and efficiency estimates in 2015 for China's coal-fired power plants, for baseline and different scenarios

	Baseline	Close subcritical commissioned before 1971	Close all subcritical and replace instantaneously with USC at 44% LHV gross average efficiency	Close all subcritical and replace instantaneously with USC at 47% LHV gross average efficiency	Raise efficiency of all subcritical PCC units by 2% points	Close pre-1991 subcritical capacity factor of post-2000 PCC 80% and post-2010 PCC 90%, others at 55%
CO_2, Mt	4192	NA	3695	3580	4066	5585
TWh, gross	4751	NA	4751	4751	4751	6479
CO_2 g/kWh, gross	882	NA	778 (total reduction of 12%)	754 (total reduction of 15%)	856 (reduction of 2.9%)	862 (reduction of 2.3%)
System efficiency, % LHV, gross	38.6	N/A	43.8	45.2	39.8	39.5

generated, and the system efficiency would rise to 43.8% LHV, gross. The efficiency assumption of 44% is intended to represent lower than a design efficiency, to take account of operating conditions over a year, as well as the likelihood that some units will have higher cooling temperatures (for instance because dry cooling has to be used). However, it is recognised that such an assumption may be considered rather conservative, so the effect of assuming a 47% LHV, gross efficiency for the replacement plants is also shown in the table.

The effect of raising the efficiency of all the subcritical plants by two percentage points is also shown in Table 4. It is assumed that fuel is saved rather than that additional power is generated. The specific emission decreases and over 120 Mt of CO_2 is predicted to be saved.

To illustrate the value of adopting a system to encourage newer, more efficient plants to operate at higher capacity factor (for example, by implementing the ECPG), another scenario was assessed. In this, supercritical and USC units from 2000 onwards are assigned higher capacity factors, pre-1991 subcritical units are closed, and remaining units are kept at 55%. The last column in Table 4 shows the assumptions used and the calculated consequences. More CO_2 is released, but more power is generated, and the system specific emission decreases compared with the baseline by 2.3%. The system efficiency would increase to 39.5% LHV, gross, or two percentage points above the OECD average for 2008. The assumptions are speculative and so the results are indicative only, but they show that a significant further benefit should be achievable from realising the full potential of the recent rapid plant build and on-going constructions through applying some form of merit order system. It would also make sense economically.

3.5 2030 Baseline

3.5.1 Initial approach – existing capacity as baseline

Outputs from the model for this approach are shown in Table 5. The capacity factor is fixed at 55%. The basis here is for a rundown of existing capacity. In China, the bulk of the capacity has

Table 5 CO_2 emissions, generation and efficiency estimates in 2030 for China's coal-fired power plants, for baseline of rundown of existing capacity					
	Baseline	Close all PCC subcritical and replace by 2030 with A-USC at 51–54% LHV gross average efficiency	As in previous column, but with replacement plants incorporating CCS	Replace 50% of pre-1996 PCC subcritical with A-USC at 51–54% LHV gross average efficiency	As in previous column, but with replacement plants incorporating CCS
CO_2, Mt	4291	3731	2688	4227	4110
TWh, gross	4723	4723	4723	4723	4723
CO_2 g/kWh, gross	909	790	569	895	870
System efficiency, % LHV, gross	37.5	43.1	43.1	38.1	38.1

been installed since the 1980s, so only a small proportion of plants would close by 2030 due to age alone. Consequently, the power generated from the surviving plants is similar to that generated in 2015. The table shows the results for a plant retirement age of 50 years, but there is little change assuming 60 years. This is demonstrated in Figure 2.

By 2030, A-USC and advanced IGCC systems will be commercially available. China already has an A-USC development programme, and advanced IGCC has also attracted interest there. The effect of replacement of all the PCC (not CFBC) subcritical capacity with A-USC at 51% (54% for A-USC lignite with drying) LHV gross efficiency is shown in the table. These efficiencies, equivalent to 48–51% LHV, net, are pitched a little lower than likely design efficiencies for the systems. The effect of advanced IGCC replacements will be very similar, so was not specifically examined. 560 Mt/y of emissions could theoretically be saved, for the same gross power generation.

China is in the middle of a programme that will probably result in all units below 300 MW being closed. There are over 40 GW of these above 100 MW, accounting for about half of the pre-1996 coal-fired capacity. The model was used to simulate replacement of 50% of the pre-1996 subcritical capacity remaining in 2030 with A-USC (*see* Table 5). Over 60 Mt of CO_2 emissions would be saved annually.

CO_2 capture and storage (CCS) could be the norm on new coal plants by the 2030s, driven by environmental policies worldwide and consequent higher carbon prices that should help make it potentially competitive with non-fossil power generation options. China has become active in CCS projects in recent years. The effect of incorporating CCS on the A-USC capacity has therefore been examined, and the results of this are also shown in Table 5. Using advanced IGCC or A-USC as the basis for CCS plants will greatly reduce the quantity of emissions to be captured. Generation and efficiency do not decrease because the model is based around gross generation. CO_2 emissions decrease by a further 1040 Mt/y, for the case with all subcritical converted to A-USC with CCS, and by about 120 Mt for the replacement of 50% of the pre-1996 subcritical capacity remaining in 2030 with A-USC plus CCS. Note that less net power would be generated as CCS consumes a considerable quantity of energy, so additional generation would be needed from somewhere to make up the lost power.

3.5.2 Including new plants

For the second assessment of the 2030 situation, plant replacements and new plants are assumed to be

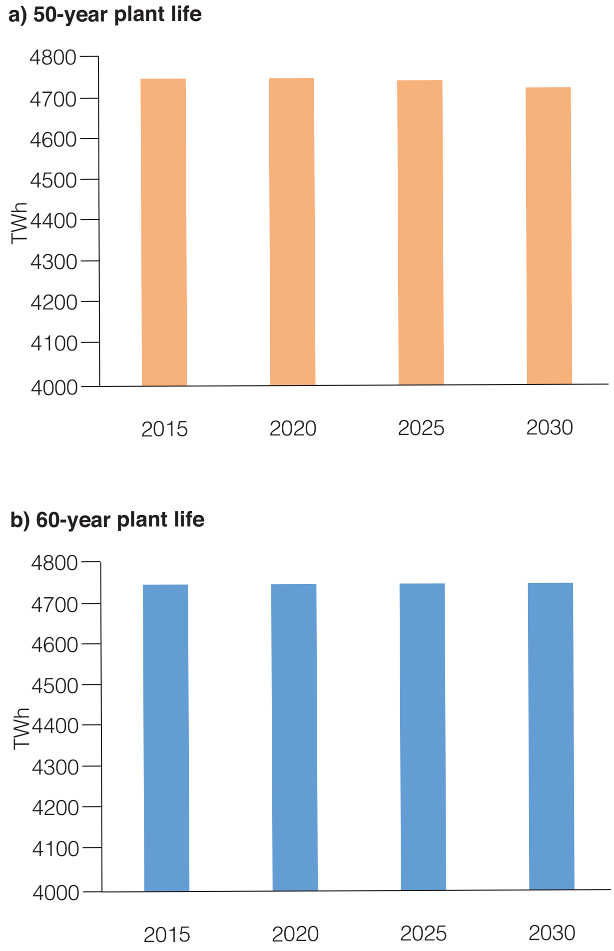

Figure 2 Effect of varying plant retirement age on calculated generation from existing capacity for China (TWh)

added between 2015 and 2030 to meet the estimated total coal capacity for 2030 of 1479 GW (*see* Section 3.1). The capacity factor was fixed across the system at 55% and plant retirement age was 50 years.

Two basic situations were compared. In the first, the model was set such that the new constructions resulted in the same proportion of subcritical plants being present in 2030 as in 2015. In the other (more realistic), all units added between 2015 and 2030 were assumed to be USC to A-USC (or IGCC) at 46% to 2020, 49% to 2025 and 51% to 2030, all LHV, gross, with three percentage points higher values than these for lignite, assuming fuel drying. Table 6 shows the results. Generation rises to 7128 TWh, and emissions, for new constructions of subcritical and USC to A-USC or IGCC, are 6252 Mt in 2030. If all the new plants are USC to A-USC and IGCC (that is, no more subcritical plants are built) the emissions become 5984 Mt/y. If CCS is incorporated with these new plants, emissions are 4461 Mt/y.

Table 6 CO_2 emissions, generation and efficiency estimates in 2030 for China's coal-fired power plants, for baseline of new constructions between 2015 and 2030

	Baseline (subcritical and supercritical new constructions after 2015)	All new constructions from 2016-2030 as USC-A-USC)	As in previous column, but with new plants incorporating CCS
CO_2, Mt	6252	5984	4461
TWh, gross	7128	7128	7128
CO_2 g/kWh, gross	877	840	626
System efficiency, % LHV, gross	38.9	40.6	40.6

4 India

4.1 Current situation

India also has a large fleet of coal-fired power plants, with 100 GW at the end of October 2011 (Mathur, 2011). Until a few years ago, all were subcritical, but now both subcritical and supercritical plants are being ordered and built. As well as the introduction of supercritical, then USC and IGCC technologies, the national low carbon growth strategy involves efficiency improvement of existing stations, renovation and modernisation of old units, and retirement of small, old and less efficient non-reheat plants (Mathur, 2011). There is a policy option to require all plants to be supercritical after the end of the 12th plan (2017). Means to achieve this that are under consideration are issue of an advisory notice to utilities to install supercritical plants only, giving priority in future coal supply permits to supercritical projects, and amending CEA regulations on required technical standards to specify supercritical conditions. Among the drivers is the optimisation of fuel, land and water usage in addition to cost reduction and reducing emissions. Steam conditions in the supercritical plants are not quite at the level of USC yet, but presumably will be shortly. Recent units using the highest conditions (supplied by BHEL) have reached 25.6 MPa/568ºC/596ºC (Sukumar, 2011).

The situation in India regarding capacity addition has been changing very rapidly during the production of this report, and many projects stated as merely planned in Coal Power were suspected actually to be under construction or even operating. The Coal Power projects listed as planned were therefore re-examined by carrying out an internet search. This showed that many were indeed under construction as of January 2012, with a number already in operation. Additional sources of information included the plant suppliers, project developers and information services such as the Economic Research India Limited Project Monitor (Project Monitor, 2012) and Infraline (2012) and publishers such as Steelguru.

Table 7 shows the assigned efficiencies and capacities of the tranches of plants for India for 2015.

4.2 Model calibration

The average plant load factor (PLF) for India's thermal power plants has increased over time but is currently fairly constant at about 77% (Mathur, 2011). India's PLF is the equivalent of the capacity factor or plant utilisation as used in this model. The oldest units can have PLFs around 40%, sometimes lower, while larger, more recent ones operate at up to 90% PLF. The high overall PLF is driven by the high demand and capacity shortages in India.

IEA generation data including autogenerators show 569 TWh in 2008 (IEA, 2010). Most recent data show 617 TWh in 2009 (IEA, 2011a). Extrapolating these two recent IEA generation figures gives an approximate estimate of 665 TWh for 2010. The calculated generation from this model in 2010 is also 665 TWh using the PLF of 77.48% for that year cited by Mathur (2011). The capacity shown by the model (from Coal Power data, corrected for known delay of opening of supercritical units) was 98 GW at the end of 2010, compared with 100 GW as of end of October 2011 from Mathur (2011). This indicated that the model provided a reasonable representation of the situation in India.

The 2010 overall system PLF of 77.48% could be reproduced using the model to calculate utilisations according to a fixed rate of decrease with plant age from a starting value of 90% (*see* Table 8). The rate of decrease was 4.5 percentage points per five years. The latter was therefore adopted for the baseline and scenario calculations, as it broadly reflected the manner of operation of the system in India and so enabled future utilisations to be estimated systematically for this country.

Table 7 Indian coal plants data				
Commissioning date	% efficiency LHV	MWe	% efficiency LHV	MWe
	Hard coal		Lignite	
SC and USC				
Up to 1970				
1971-1975				
1976-1980				
1981-1985				
1986-1990				
1991-1995				
1996-2000				
2001-2005				
2006-2010				
2011-2015	41	48380	40	1320
TOTALS		**48380**		**1320**
SUBCRITICAL				
Up to 1970 + ⩽100 MW (no date)	24	3850	22	792
1971-1975	25	2663	24	280
1976-1980	28	5530	24	540
1981-1985	30	9985	29	320
1986-1990	31	15115	29	810
1991-1995	31	10188	30	1330
1996-2000	33	7845	25	380
2001-2005	34	8817	30	795
2006-2010	35	27337	29	1335
2011-2015	36	42060		
TOTALS		**133390**		**6582**

Efficiency basis: all LHV, gross, estimated annual average
Situation in 2015; based on operating or believed under construction, less those expected to close before end 2015

4.3 Baseline CO_2 emissions (2015)

The basis of the capacity factors was described in the previous section and the values for the 2015 baseline year are shown in Table 9 and Figure 3. The system utilisation is predicted to be higher (at 81.2%) than in 2010 because by 2015 there will be a large proportion of very recent units operating, with nearly 50% of estimated 2015 total capacity commissioning after 2010.

The baseline emissions, generation and efficiency estimates for the 2015 baseline are shown in Table 10. The predicted average fleet efficiency is 35.1% LHV, gross basis, compared with the

Table 8 India – coal unit utilisations in 2010 obtained using 4.5% pts decrease/five years from 90% at first operation	
Year of first operation	Utilisation, %
Up to 1970	53.7
1971-1975	58.2
1976-1980	62.8
1981-1985	67.3
1986-1990	71.8
1991-1995	76.4
1996-2000	80.9
2001-2005	85.5
2006-2010	90.0
All above	77.5

Table 9 India – coal unit utilisations in baseline year 2015 obtained using 4.5% pts decrease/five years from 90% at first operation	
Year of first operation	Utilisation, %
Up to 1970	49.1
1971-1975	53.7
1976-1980	58.2
1981-1985	62.8
1986-1990	67.3
1991-1995	71.8
1996-2000	76.4
2001-2005	80.9
2006-2010	85.5
2011-2015	90.0
All above	81.2

average efficiency in the OECD area in 2008 for coal plants of 37.5% LHV, gross. The fleet efficiency values in 2005 and 2010 shown in the model were 30.4% and 31.7% LHV, gross. This shows the improvement over time that is occurring and will continue to occur as new units, particularly the supercritical ones, are deployed. The estimated CO_2 emissions in 2015 are 1.32 Gt.

4.4 Scenarios from 2015 baseline

India continues to require more power than it can generate, and, in the past, closure of old capacity has not generally been regarded as a practical option for system efficiency improvement. In the future, some old non-reheat units of small capacity will probably be closed, but most emphasis on subcritical plants will consist of renovation and modernisation. Such programmes have been applied to a number of plants in the past and further actions of this type are planned. According to the CEA, 18.965 GW are being renovated under the 11th five-year economic plan (to 2012) and 4.971 GW are being renovated under the 12th plan (to 2017) (Mathur, 2011). This is a total of 23.936 GW by 2017. The data in the model show 22 GW of subcritical capacity dating from 1985 and earlier, and in 2015, all of these will be at least 30 years old. The 22 GW ties in quite well with the capacity earmarked for R & M plans. The model has therefore been used to examine the effect of a two percentage point efficiency improvement for these 22 GW of plants. The results are included in Table 10. This measure should save 11 Mt/y of CO_2, for the same power generated. In practice, more generation would probably occur, but the specific emissions of CO_2 would still be reduced. The table also shows the predicted CO_2 emissions saved if all subcritical units were to be improved in efficiency by two percentage points (57 Mt/y).

The effect of an overnight replacement of all the subcritical plants by supercritical units was also examined. A reference from the Central Electricity Authority in India suggests that supercritical plants will have an efficiency advantage over subcritical units of two percentage points (Mathur, 2011). However, another reference from the CEA suggests that the gain over current 500 MW subcritical systems would be five percentage points (Thakur, 2011). Although in India, all plants tend to have lower efficiencies than in many other parts of the world because of the high ash coals and high ambient temperatures, a five percentage points gain in moving to supercritical appears likely.

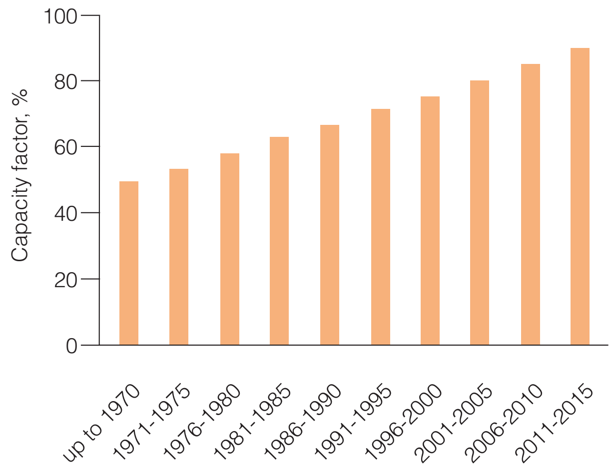

Figure 3 Calculated capacity factors of plant tranches for India in 2015

Consequently, here we have assumed that the supercritical units would achieve an efficiency of 41% LHV, gross, on an annual basis for hard coals, and 40% on lignites. This is the same as the assumed values used in the model for the supercritical units that are currently being installed and on order in India. The annual CO_2 emissions were predicted to fall from 1315 to 1125 Mt (*see* Table 10). Specific emissions would be reduced by 14%. If USC conditions were used (steam temperatures of 600ºC/620ºC), the improvement would be even greater, at 18%, also shown in the table. This case assumes that USC parameters could push the efficiency up a further three percentage points.

Table 10 CO_2 emissions, generation and efficiency estimates in 2015 for India's coal-fired power plants, for baseline and different scenarios

	Baseline	Raise efficiency of pre-1986 subcritical by 2% points	Raise efficiency of all subcritical PCC units by 2% points	Close all subcritical and replace instantaneously with SC at 41% LHV gross average efficiency	Close all subcritical and replace instantaneously with USC at 44% LHV gross average efficiency
CO_2, Mt	1315	1304	1258	1125	1070
TWh, gross	1349	1349	1349	1349	1349
CO_2 g/kWh, gross	975	967 (reduction of 0.8%)	932 (reduction of 4.4%)	834 (reduction of 14%)	793 (reduction of 18%)
System efficiency, % LHV, gross	35.1	35.3	36.6	41.0	43.0

Table 11 CO_2 emissions, generation and efficiency estimates in 2030 for India's coal-fired power plants, for baseline of rundown of existing capacity

	Baseline	Close all subcritical and replace by 2030 with A-USC at 48–51% LHV gross average efficiency	As in previous column, but with replacement plants incorporating CCS
CO_2, Mt	1247	941	367
TWh, gross	1252	1252	1252
CO_2 g/kWh, gross	996	752	293
System efficiency, % LHV, gross	34.3	45.4	45.4

4.5 2030 Baseline

4.5.1 Initial approach – existing capacity as baseline

Outputs from the model for this approach are shown in Table 11. The basis here is for a rundown of existing capacity with retirements at 50 years. The capacity factor was fixed overall at the 81.2% calculated for 2015. Generation is consequently lower than in 2015.

Like China, India also has A-USC and advanced IGCC development plans. By 2030, the technologies will be commercially available from several foreign suppliers also. The effect of replacement of all the subcritical capacity with A-USC at 48% (51% for A-USC lignite with drying) LHV gross efficiency is shown in the table. These efficiencies, equivalent to 45–48% LHV, net, are placed a little lower than likely design efficiencies and take account of Indian coals and climate. The effect of advanced IGCC replacements will be fairly similar, so was not specifically examined for India. The replacement of all the surviving subcritical plants would save about 300 Mt/y of CO_2 emissions.

CO_2 capture and storage (CCS) is likely to be required on new coal-fired plants by the 2030s, driven by environmental policies worldwide and consequent higher carbon prices that should help make it potentially competitive with non-fossil power generation options. The effect of including CCS on the A-USC capacity has been examined, and the results of this are also shown in Table 11. Generation and efficiency do not decrease because the model is based around gross generation. CO_2 emissions decrease further by around 570 Mt/y.

4.5.2 Including new plants

For the second assessment of the 2030 situation, plant replacements and new plants are assumed to be added between 2015 and 2030 to meet an estimated or assumed total capacity or capacity growth rate. The CEA anticipates an additional 80 GW of all types of capacity between 2012 and 2017 (12th Plan) and provisionally a further 100 GW by 2022 (13th Plan) (Mathur, 2011). The US EIA estimates that coal capacity in India will be 171 GW in 2035 (EIA, 2011), but this appears conservative (we have more than this for 2015 (190 GW), based largely on the Coal Power data). For this variant of the 2030 assessment, the capacity has been set at 240 GW, based on the 2015 estimate plus 50% of the 13th Plan additions. Clearly there is great uncertainty in establishing a realistic value. The capacity growth rate needed to reach that capacity was 1.58% per year between 2015 and 2030. The capacity factor was again fixed across the system at 81.2%.

Two basic situations were compared. In the first, the model was set such that the new constructions

Table 12 CO_2 emissions, generation and efficiency estimates in 2030 for India's coal-fired power plants, for baseline of new constructions between 2015 and 2030

	Baseline (subcritical and supercritical new constructions after 2015)	All new constructions from 2015-2030 as USC, A-USC or IGCC	As in previous column, but with new plants incorporating CCS
CO_2, Mt	1664	1586	1281
TWh, gross	1707	1707	1707
CO_2 g/kWh, gross	975	929	750
System efficiency, % LHV, gross	35.0	36.8	36.8

resulted in the same proportion of subcritical plants being present in 2030 as in 2015. The SC plants were USC to A-USC, with efficiencies at 44% to 2020, 46% to 2025 and 48% to 2030, all LHV, gross, all with three percentage points higher for lignite, assuming fuel drying. In the other, all units added between 2015 and 2030 were assumed to be USC to A-USC (or IGCC), so no new subcritical units would be built. Table 12 shows the results. Generation rises to 1707 TWh because of the additional capacity. Emissions, for new constructions of subcritical and USC to A-USC or IGCC, are 1664 Mt in 2030. If all the new plants are USC to A-USC and IGCC (that is if no more subcritical plants are built) the emissions become 1586 Mt/y. If CCS is incorporated with these new plants, emissions are 1281 Mt/y.

5 South Africa

5.1 Current situation

Most of South Africa's power stations are coal fired. There is a significant capacity of subcritical units, and Eskom, the nationalised generation company, has recently embarked on a programme of installing supercritical plants, using steam conditions of 24.1 MPa/560ºC/570ºC. About 4 GW of subcritical units that were mothballed are also being brought back into operation. Rapidly growing power needs are driving these developments. Eskom plans to increase its total capacity to 80 GW by 2026 (Eskom, 2010) It is estimated that this will include about 75 GW of coal, as there are currently about 5 GW power plants using other fuels (Eskom, 2008). The best coals are exported, so the country's power plants use high ash (up to 30%) and high sulphur bituminous coals. Plants all operate as far as possible on base load because of the current small reserve capacity. The combination of low quality coals and high ambient temperatures limits the efficiency of the plants and, in addition, in some areas the need to conserve water supplies dictates that air cooled systems be used. This has made the move to supercritical conditions even more important. Medupi, the first 6x794 MW (gross) supercritical plant under construction, and its twin plant, Kusile, will both use air cooled condensers (Fouilloux and Otto, 2009).

To obtain the capacity in 2015 for the baseline, the data from Coal Power as of December 2011 was adjusted, assuming that all the remaining units mothballed at Camden, Komati and Grootvlei would be back in service by that date. About 2.2 GW at these three stations was reported as re-commissioned by Eskom by 2010 (Eskom, 2010).

The dates for commissioning of the last units at the two new supercritical stations are given as 2014-17, depending on the source. Coal Power information indicated five of the Medupi and four of the Kusile units would be running by 2015, and it was decided to use this as input to the model for that date. The capacities in Coal Power were adjusted slightly to those cited by Alstom and Eskom (for example, Fouilloux and Otto,). Total capacity in 2015 is over 46 GW, of which 7.2 GW is supercritical, the latter reaching 9.5 GW within a year or two of the above date.

Table 13 shows the assigned efficiencies and capacities of the tranches of plants for South Africa.

5.2 Model calibration

IEA generation data show 241 TWh in 2008 (IEA, 2010) and 232 TWh in 2009 (IEA, 2011a). A model overall capacity factor of 73.3% (fixed for all coal units) was found to give a calculated generation of 241 TWh for 2010. The high system utilisation was consistent with the small capacity margin and indicated that the model should provided a reasonable representation of the situation in South Africa.

5.3 Baseline CO_2 emissions (2015)

The emissions, generation and specific emissions for the 2015 baseline are shown in Table 14. The predicted average fleet efficiency is 36.4% LHV, gross basis, compared with the average efficiency in the OECD area in 2008 for coal plants of 37.5% LHV, gross. The fleet efficiency shown in the model for 2010 was 35.7% LHV, gross. The increase in overall efficiency will stem from the addition of the supercritical plants, currently under construction. The estimated CO_2 emissions in 2015 are 277 Mt and generation is 296 TWh.

Table 13 South African coal plants data

Commissioning date	% efficiency LHV	MWe	% efficiency LHV	MWe
	Hard coal		Lignite	
SC and USC				
Up to 1970				
1971-1975				
1976-1980				
1981-1985				
1986-1990				
1991-1995				
1996-2000				
2001-2005				
2006-2010				
2011-2015	42	7153		
TOTALS		**7153**		
SUBCRITICAL				
Up to 1970	30	1762		
1971-1975	33	3300		
1976-1980	35	6400		
1981-1985	37	4809		
1986-1990	37	10099		
1991-1995	37	4760		
1996-2000	37	3451		
2001-2005	38	913		
2006-2010	33	2050		
2011-2015	33	1450		
TOTALS		**38994**		

Efficiency basis: all LHV, gross, estimated annual average
Situation in 2015; based on operating or believed under construction, less those expected to close before end 2015

5.4 Scenarios from 2015 baseline

The effect on CO_2 emissions in 2015 of raising the efficiency of all of the subcritical units by two percentage points is shown in Table 14. For the same amount of power generated, 13 Mt less are produced and the specific emissions fall by more than 4%. For the same capacity factors, if all were instantaneously replaced by supercritical units of 42% LHV, gross, efficiency, the specific emissions would be reduced by 13%. Alternatively, replacement with USC at 45% would reduce them by 18%.

Table 14 CO_2 emissions, generation and efficiency estimates in 2015 for South Africa's coal-fired power plants, for baseline and different scenarios

	Baseline	Raise efficiency of all subcritical PCC units by 2% points	Close all subcritical and replace instantaneously with SC at 42% LHV gross average efficiency	Close all subcritical and replace instantaneously with USC at 45% LHV gross average efficiency
CO_2, Mt	277	264	240	227
TWh, gross	296	296	296	296
CO_2 g/kWh, gross	935	892 (reduction of 4.6%)	811 (reduction of 13%)	765 (reduction of 18%)
System efficiency, % LHV, gross	36.4	38.2	42.0	44.5

5.5 2030 Baseline

5.5.1 Initial approach – existing capacity as baseline

Outputs from the model for this approach are shown in Table 15. The basis here is for a rundown of existing capacity with retirements at 60 years. However, since the last three supercritical units at Medupi and Kusile are certain to be operating by 2017, and perhaps earlier, this capacity has been included. A plant retirement age of 60 years was used, as no units are likely to be closed at 50 years in South Africa. The plant utilisations were kept at 73.3%. On the above basis, generation in 2030 is 300 TWh, and CO_2 emissions are 280 Mt.

The effect of replacement of the entire subcritical capacity with A-USC at 49% LHV gross efficiency in 2030 is shown in the table. This efficiency, equivalent to 46% LHV, net, is placed a little lower than likely design efficiency and takes account of South Africa's climate and of the coals that are used for power generation. The replacement of the subcritical plants would save over 60 Mt/y of CO_2 emissions.

CO_2 capture and storage (CCS) will be needed on new coal-fired units by the 2030s, driven by environmental policies worldwide and consequent higher carbon prices that should help make it potentially competitive with non-fossil power generation options. The effect of incorporating CCS on the new A-USC capacity has been examined, and the results of this are also shown in Table 15. CO_2 emissions decrease by around a further 150 Mt/y.

Table 15 CO_2 emissions, generation and efficiency estimates in 2030 for South Africa's coal-fired power plants, for baseline of rundown of existing capacity

	Baseline	Replace all subcritical in 2030 with A-USC at 49% LHV gross average efficiency	As in previous column, but with replacement plants incorporating CCS
CO_2, Mt	280	217	68
TWh, gross	300	300	300
CO_2 g/kWh, gross	934	724	226
System efficiency, % LHV, gross	36.5	47.1	47.1

5.5.2 Including new plants

For the second assessment of the 2030 situation, plant replacements and new plants are assumed to be added between 2015 and 2030 to meet an estimated total capacity in 2030. An estimate of 75 GW of total coal capacity in 2026 was suggested in Section 5.1, based on Eskom's plans. For the emissions estimates, the capacity growth was set so as to achieve this capacity in 2030. The growth rate was 2.94% per year from 2015 to 2030.

As for the other countries, two basic situations were compared. In the first, the model was set such that the new constructions resulted in the same proportion of subcritical plants being present in 2030 as in 2015. The efficiencies assumed for the SC and above plants were in this case 42% to 2020, 45% to 2025 and 49% to 2030, all LHV, gross. In the other, all units added between 2015 and 2030 were assumed to be USC to A-USC (or IGCC), so no new subcritical units would be built. Table 16 shows the results. Generation rises to 482 TWh because of the additional capacity. Emissions, for new constructions of subcritical and USC to A-USC or IGCC, are 443 Mt in 2030. If all the new plants are USC to A-USC and IGCC (that is, no more subcritical plants are built) the emissions become 416 Mt/y. If CCS is incorporated with these new plants, emissions are reduced to 294 Mt/y.

Table 16 CO_2 emissions, generation and efficiency estimates in 2030 for South Africa's coal-fired power plants, for baseline of new constructions between 2015 and 2030

	Baseline (subcritical and supercritical new constructions after 2015)	All new constructions from 2015-2030 as USC,A-USC or IGCC	As in previous column, but with new plants incorporating CCS
CO_2, Mt	443	416	294
TWh, gross	482	482	482
CO_2 g/kWh, gross	919	865	611
System efficiency, % LHV, gross	37.1	39.4	39.4

6 USA

6.1 Current situation

The USA has a large coal-fired power plant fleet, consisting of subcritical and supercritical units. Two thirds of the plants are no larger than 350 MW. Total coal-fired capacity is currently about 325 GW. Much of it dates from the 1960s and 1970s. Subcritical units have been constructed right up to the present, although in lesser numbers since the mid-1980s. Interest in supercritical plants waned during the 1980s, and there was a period of about 25 years when few were constructed. Something of a revival occurred in the mid-2000s, with the installation of supercritical and USC units from foreign suppliers.

US DOE information shows that the range of efficiencies of the whole coal fleet is large, and that there are examples of subcritical units with high efficiency and supercritical units with relatively low efficiency (*see* Table 17). Part of the difference in the average efficiencies for different age groups within the subcritical fleet may come from extent of application of emission controls. The average efficiency of the supercritical units in different age tranches is about 3–4 percentage points higher than the average for the subcritical units in the same age range. The National Electric Energy Data System (NEEDS) database, which contains heat rates for individual units (EPA, 2010) also shows wide variations for apparently similar plants.

US DOE information shows that the average efficiency of the top ten per cent of the fleet in 2008 was 37.6%, HHV, net, while the average efficiency of the whole fleet was 32.5%, HHV. It was concluded from this that better maintenance and operating practice could raise the average efficiency to 35.2%, HHV, net, and that the retirement of smaller, older units and improvements within the better units could increase this average to 36% (DiPietro and Krulla, 2010).

Table 17 Analysis of US coal-fired units with capacity factor greater than 50% in 2007 (Nichols and others, 2008)

Steam cycle type	Age band	Number of units	Nameplate capacity, MW	Generation, TWh	Average efficiency, %, HHV, net	Efficiency range	Efficiency top 10%
Subcritical	Up to 1969	410	77,789	447	31.3	19.1-40.9	36.3
	1970-1989	273	127,675	824	31.4	20.5-38.7	36.3
	1990-2007	27	7,477	51	29.9	21.1-37.6	35.9
Subcritical subtotal		710	212,942	1,322	31.3	19.1-40.9	36.4
Supercritical	Up to 1969	34	19,467	114	34.9	22.5-40.1	38.8
	1970-1989	74	60,169	398	35.1	29.8–41.0	39.1
	1990-2007	1	1,426	10	40.2	N/A	N/A
Supercritical subtotal		109	81,061	522	35.1	22.5-41.0	39.3
Grand total		819	294,003	1,844	31.8	19.1-41.0	37.4

Table 18 USA coal plants data

Commissioning date	% efficiency LHV	MWe	% efficiency LHV	MWe
	Hard coal		Lignite	
SC and USC				
Up to 1970	37	16843		
1971-1975	39	28824		
1976-1980	39	8533	38	793
1981-1985	39	1968		
1986-1990	39	1300		
1991-1995	40	1426		
1996-2000				
2001-2005				
2006-2010	43	5825	43	1720
2011-2015	44	3635		
TOTALS		**68354**		**2513**
SUBCRITICAL				
Up to 1970 (units ⩽100 MWe)	31	11725	30	90
Up to 1970 (units >100 MWe)	35	76059	34	445
1971-1975	36	30799	36	2816
1976-1980	36	50288	36	3934
1981-1985	36	41772	36	4015
1986-1990	36	14240	36	2100
1991-1995	36	6230	36	150
1996-2000	38	2387		
2001-2005	40	2992	38	440
2006-2010	40	6917	38	699
2011-2015	40	3990		
TOTALS		**247399**		**14689**
IGCC				
1996-2000	46	320		
2001-2005				
2006-2010				
2011-2015	48	710	48	669
TOTALS		1030		669

Efficiency basis: all LHV, gross, estimated annual average
Situation in 2015; based on operating or believed under construction, less those expected to close before end 2015

Table 18 shows the assigned efficiencies for the tranches of plants for the USA. Of the pre-1971 units, those of 100 MW or less are separately shown from the larger ones. The average efficiency is 36.2% gross, LHV for units to 2010, a value consistent with the published fleet efficiency of 32.5%, net, HHV (DiPietro and Krulla, 2010).

6.2 Model calibration

Adjusting the utilisations of the tranches in the present model was carried out to arrive at an estimated gross generation in 2005 of 2068 TWh. This equals the figure published by the IEA for the year 2006 (IEA, 2010) for electricity generated from coal in electricity plants. It was assumed that the utilisations of the plant groups were 90% initially, and the rate of decrease in utilisation was the parameter adjusted to reproduce the generation of 2068 TWh in 2005. A 2.6 percentage points decrease in utilisation over each five years was needed to achieve this, and it corresponded to a system utilisation of 76.0%. Estimated CO_2 emissions were 1961 Mt. The official US National Greenhouse Gas Inventory published by the EPA shows emissions of 1984 Gt from coal in electricity plants for 2005 (EPA, 2011), so agreement was satisfactory. However, the average system capacity factor was higher than the value shown by DiPietro and Kruller (2010). In this regard, it is noted that DiPietro and Kruller include also what they call average *load factors*, based on net generation, of 83% and 75% for the top decile and rest of fleet. These load factors are close to the system capacity factor found here to reach the alignment of emissions and gross generation in and close to 2005.

DiPietro and Kruller show the load factor as defined by the net generation in a year divided by the net capacity rating multiplied by the plant's operating hours during the year. Capacity factor is normally defined analogously, whether on net or gross. It is possible that the convention used for the calculations of the capacity factor in the USA may differ. Clearly, some aspects remain unclear, but the model is working correctly. The source of differences may lie partly in the apparently larger difference between net and gross capacities of coal plants in the USA than for some other countries. This is for example illustrated in a document from the Tennessee Valley Authority (TVA, 1995) that showed that the summer net capacity of their 59 active coal units was14,685 GW in 1995, compared with a gross capacity in Coal Power of 16,560 MW. The difference implies auxiliary power usage of 11.3% of gross power.

As a further test of the model to reflect more recent developments, adjustment of utilisation against the generation for 2009 shown in IEA (2011a) (1893 TWh) was also carried out. Data for 2010 are not yet available, so these values were used to validate the model output for 2010. The calculated emissions for 2010 were 1780 Gt. The EPA (2011) figure is 1748 Gt for 2009 for coal-fired electricity generation. The utilisations were therefore adjusted slightly further so that the estimate for 2010 emissions were the same. The decrease in utilisation from the starting values was four percentage points each five years. This gave a system utilisation of 65.2% and gross generation of 1860 GWh.

A judgement then had to be made on whether to assume a continuing drop in system utilisation. The 2009 situation was affected by the severe economic recession. Before then, the coal-fired generation system in the USA appears to have operated at a fairly constant capacity factor, as shown by the emissions during the period 2005-08 remaining at 1.95–1.99 Gt throughout, with no consistent rise or fall. The decision was taken to assume that the system utilisation would return to the 76% determined above for 2005. A capacity factor fixed at that value across the system was therefore adopted for all the assessments.

6.3 Baseline CO_2 emissions (2015)

The basis of calibration was described in the previous section. The baseline emissions, generation,

Table 19 CO_2 emissions, generation and efficiency estimates in 2015 for USA coal-fired power plants, for baseline and different scenarios

	Baseline	Close subcritical commis-sioned before 1971	Close pre-1971 subcritical and replace instant-aneously with USC at 44% LHV gross average efficiency	As previous column plus raise efficiency of later subcritical units by 2% points	Close pre-1971 subcritical and replace instant-aneously with USC at 47% LHV gross average efficiency	As previous column plus raise efficiency of later subcritical units by 2% points
CO_2, Mt	2093	1510	1966	1909	1937	1880
TWh, gross	2228	1640	2228	2228	2228	2228
CO_2 g/kWh, gross	939	921 (reduced by 1.9%)	882 (total reduction of 6.1%)	857 (total reduction of 8.7%)	869 (total reduction of 8.2%)	844 (total reduction of 10%)
System efficiency, % LHV, gross	36.4	37.2	38.7	39.9	39.3	40.5

specific emissions and system efficiency for the 2015 baseline are shown in Table 19. Estimated CO_2 emissions are about 2.1 Gt. The predicted average fleet efficiency in 2015 is 36.4% LHV, gross basis. The predicted specific emissions of CO_2 for the US coal-fired fleet in 2015 are 3.4% higher than expected for China, which is of course investing heavily in new supercritical and ultra-supercritical units and closing old, inefficient small units.

6.4 Scenarios from 2015 baseline

For 2015, the most appropriate improvement options will be improvement of operation and maintenance procedures in the better subcritical plants and/or some closure of plants in the lowest performing category. A number of plant retirements have been announced recently because of more demanding emissions requirements being uneconomic to meet. The effect of an instantaneous closure of all subcritical plants dating before 1971 is shown in Table 19. System efficiency rises to 37.2%, LHV, gross. This is an extreme example, and such a course of action would be rather a blunt instrument, but illustrates the potential specific emissions saving of 1.9%. Output from the rest of the coal system would probably rise to some extent, and this would probably raise efficiency a little further. Also shown is the effect of instantaneously replacing the pre-1971 subcritical plants with an equal capacity of state-of-the-art USC plants of 44% gross LHV operating efficiency (43% for lignite plants). The drop in specific emissions is much larger when the USC replacements are added (total of over 6%). The efficiency assumption of 44% for USC replacements represents lower than a design efficiency, to take account of operating conditions over a year. However, such an assumption could be considered rather conservative, so the effect of assuming a 47% LHV, gross efficiency for the replacement plants is also shown in the table. The specific emissions saving would be increased.

An additional strategy could involve raising the efficiency of the more recent subcritical plants. An illustration of the effect of a two percentage point change is shown in the table. It is assumed that fuel is saved rather than that additional power is generated. The specific emission decreases further.

6.5 2030 Baseline

6.5.1 Initial approach – existing capacity as baseline

The plant retirement age becomes important for this baseline year. The 50 years assumed for the 2015 baseline means that no units close until after that date. However, for the same plant life assumption, the pre-1981 plants are offline by 2030. In practice, more plants are likely to be constructed, and this is explored in Section 6.5.2. Utilisation was kept at 76% throughout. Some of the model outputs are shown in Table 20. The basis here is for a rundown of capacity, so the power generated and associated emissions are much lower than at the starting point in 2015. For a 50-year plant retirement age, system efficiency is 36.4% LHV, gross. For a 60-year plant life, system efficiency is 36.1% LHV, gross.

The USA has its own A-USC and advanced IGCC programmes to develop power generation efficiency to higher levels. The model has been used to assess the potential benefit from replacing all the surviving pre-2001 subcritical and supercritical units (most of total capacity surviving in 2030) with such systems. Table 20 shows that very major savings in emissions would ensue (approximately 150–400 Mt/y, depending on assumptions for the retirement age of plants, which affects the capacity regarded as replaced).

CO_2 capture and storage (CCS) demonstrations are planned in the USA, with US DOE support. Such projects, if successfully completed, could pave the way for commercial deployment of CCS by 2030. Using advanced IGCC or A-USC as the basis for CCS plants would greatly reduce the quantity of emissions to be captured. The model has been used to determine the further saving in emissions of including CCS (at 90% capture rate) on the A-USC or advanced IGCC systems, and the results of this are also shown in Table 20. CO_2 emissions decrease further by approximately 300–800 Mt/y, depending on assumptions for the retirement age of plants. The fleet specific emissions are estimated to be considerably lower than the US EPA-proposed CO_2 emissions limit of 1000 lb/MWh (gross), equivalent to 454 g/kWh (gross) (EPA, 2012). Note that the additional auxiliary power demands of CO_2 capture and storage do not appear in the table as the efficiency and power are expressed on a gross generated basis.

6.5.2 Including new plants

For the second assessment of the 2030 situation, plant replacements and new plants are assumed to be added between 2015 and 2030 to meet an estimated total capacity in 2030. The US Energy

Table 20 CO_2 emissions, generation and efficiency estimates in 2030 for USA coal-fired power plants, for baseline of rundown of existing capacity

	Baseline 50-year life/ 60 year life	Replace all pre-2001 PCC units with A-USC or advanced IGCC at 51–54% LHV, gross efficiency 50-year life/60-year life	As in previous column, but with replacement plants incorporating CCS 50-year life/60-year life
CO_2, Mt	648/1450	494/1055	192/248
TWh, gross	689/1528	689/1528	689/1528
CO_2 g/kWh, gross	940/949	717/690	278/162
System efficiency, % LHV, gross	36.4/36.1	47.8/49.6	47.8/49.6

Table 21 CO_2 emissions, generation and efficiency estimates in 2030 for USA coal-fired power plants, for baseline of constant capacity to 2030

	Baseline (subcritical and supercritical new constructions after 2015 to match closing capacity) 50-year life/60-year life	All replacements from 2016-2030 as USC-A-USC) 50-year life/60-year life	As in previous column, but with new plants incorporating CCS 50-year life/60-year life
CO_2, Mt	1924/2026	1752/1918	758/1497
TWh, gross	2228/2228	2228/2228	2228/2228
CO_2 g/kWh, gross	863/909	786/861	340/672
System efficiency, % LHV, gross	39.6/37.6	43.5/39.7	43.5/39.7

Information Administration Annual Energy Outlook early release for 2012 (EIA, 2012) shows a constant level of coal-fired electricity plant capacity to 2030. Consequently, in the additional analysis carried out to model this situation, the capacity growth was set to zero, new units being added purely for making up retiring units. Capacity factor was kept at 76% throughout.

Two basic situations were compared. In the first (baseline), the model was set such that the replacement units resulted in the same proportion of subcritical plants being present in 2030 as in 2015. The efficiencies assumed for the SC and above plants were in this case 46% to 2020, 49% to 2025 and 51% to 2030, all LHV, gross, all with three percentage points higher for lignite, assuming fuel drying. In the other, all replacements added between 2015 and 2030 were assumed to be USC to A-USC (or IGCC), so no new subcritical units would be built. Table 21 shows the results. Generation remains at the same level as in 2015 (2228 TWh), regardless of plant retirement age. Emissions are lower than the baseline in 2015, in all the cases examined here. Greater emissions reductions naturally follow if no subcritical plants are built, and CCS (at 90% capture rate) increases the benefit. Benefits are greater for the earlier plant retirement age as there are more replacements to maintain total capacity. The additional auxiliary power demands of CO_2 capture and storage do not appear as the efficiency and power are expressed on a gross generated basis.

7 Australia

7.1 Current situation

Most of Australia's power stations are coal fired. There is a significant capacity of subcritical units (26 GW, including 7 GW lignite fired) and nearly 3 GW of hard coal-fired supercritical capacity, commissioned during the 2000s. Most of the hard coal-fired subcritical capacity dates from the 1980s and first half of the 1990s, and 60% of this capacity is from unit sizes of 500 MW and larger (note that there are about 2.5 GW of subbituminous coal-fired units categorised within the black coal units in the present analysis). As in many countries with mature coal-fired steam plant, turbine upgrades to improve performance of a number of the subcritical units are in progress in Australia (*see, for example*, Hitachi, 2006). Although, as in many developed countries, it is proving difficult to get new coal-fired power projects off the ground (another 2 GW of supercritical is planned), there remains interest in IGCC and CO_2 capture and storage with a number of projects still active or in prospect. An emissions tax and coal mining tax are being introduced by the federal government during 2012, potentially putting pressure on coal-fired generation in the country to further modernise.

Lignite in Victoria is an extremely accessible, low-cost resource, but there is increasing urgency in calls to improve the lignite power plants using it to reduce their CO_2 emissions. These plants are mostly fairly old, and have very low efficiencies. However, they are very heavily used. One method to improve lignite plants is to incorporate fuel drying using low grade heat effectively (*see, for example,* IEA, 2007, a report prepared for the IEA by the Clean Coal Centre). However, other options under consideration for the Latrobe Valley lignite stations include phased closure of the oldest units and greater use of natural gas. Hazelwood has eight units of 200 MW, dating from 1964 to 1971. The newest units in the Latrobe Valley, at Loy Yang B station, were commissioned in the 1990s. Some new CFBC projects are in prospect but omitted from this analysis as they have been selected only recently specifically for firing lower quality coals, and replacement or upgrading would be inappropriate.

Table 22 shows the assigned efficiencies and capacities of the tranches of plants for Australia.

7.2 Model calibration

IEA generation data (IEA, 2010) shows 198 TWh in 2008 and 188 TWh in 2009, but 203 TWh for 2009 in IEA (2011a). A model overall capacity factor of 73.4% (fixed for all coal units) was found to give a calculated generation of 188 TWh for 2010. The calculated CO_2 emissions were 184 Mt. The national greenhouse gas inventory tables for Australia show CO_2 emissions from solid fuels used for electricity and heat production of 184 Mt for 2009 and fuel input of 2.031 EJ (HHV) (DCCEE, 2011). The model showed fuel input of 1.903 EJ (LHV). This demonstrated the close agreement of the model with the reported data. System efficiency was 35.6% LHV, gross. The national inventory data shows that, for electricity and heat production, solid fuel use and emissions were almost constant over the period from 2005 to 2008, then increased by only 2% from 2008 to 2009. The capacity factor of 73.4% was therefore maintained for the assessments.

The same system capacity factor 73.4% could be achieved by assuming 90% utilisation for new plants with a declining utilisation of 3.55 percentage points over each five years. Applying this method could in principle allow future utilisations to be estimated systematically in the scenario assessments, but this would not reflect the way the Australian fleet is used. For example, in 2004, the percentage capacity factor of the lignite plants was in the high 80s, and for many of the larger black coal-fired units around that year it was over 80% (Coal Power data). Consequently, a fixed capacity factor of 73.4% was used in the evaluations.

Table 22 Australian coal plants data				
Commissioning date	% efficiency LHV	MWe	% efficiency LHV	MWe
	Hard coal		Lignite	
SC and USC				
Up to 1970				
1971-1975				
1976-1980				
1981-1985				
1986-1990				
1991-1995				
1996-2000				
2001-2005	42	2190		
2006-2010	43	750		
2011-2015				
TOTALS		**2940**		
SUBCRITICAL				
Up to 1970	30	948	26	1750
1971-1975	36	2520	30	920
1976-1980	36	4147		
1981-1985	38	5167	33	2355
1986-1990	38	2720	34	1045
1991-1995	38	2480	34	500
1996-2000	38	660	34	500
2001-2005	30	150		
2006-2010	40	447		
2011-2015				
TOTALS		**19239**		**7070**

Efficiency basis: all LHV, gross, estimated annual average
Situation in 2015; based on operating or believed under construction, less those expected to close before end 2015

7.3 Baseline CO_2 emissions (2015)

The basis of calibration was described in the previous section. The baseline emissions, generation and specific emissions for the 2015 baseline are shown in Table 23. The estimated emissions and generation are the same as for 2010 because the same capacity factor is assumed and there are no major projects commissioning between 2010 and 2015. The predicted average fleet efficiency in 2015 is 35.6% LHV, gross basis (the same as for 2010).

7.4 Scenarios from 2015 baseline

For 2015, as the larger subcritical units are already improved or in the process of being improved, the remaining improvement options will be some closure of plants in the lowest performing category. The hard coal and lignite units dating from before 1971 are mainly small units, a number having no reheat. The 200 MW lignite units at Hazelwood have been considered for closure in recent years because of their low efficiency and high emissions, and, although it would clearly be infeasible to shut them all by 2015, the model provides an illustration of the potential emissions benefits at some stage over the next ten or so years. Table 23 shows the effect of closing all pre-1971 subcritical units, which includes seven of the eight units at Hazelwood. System efficiency rises to 36.7% LHV, gross, and the specific emissions decrease by 3.5%. In practice, generation may not decrease, as other coal units may take up the system load, so the emissions are also scaled in the table to the same generation as for the baseline. If gas-fired or other systems compensate, the emissions will be lower than the 177 Gt shown for the latter assumption. Also shown is the effect of instantaneously replacing these plants with an equal capacity of USC plants of 44% gross LHV operating efficiency (43% for lignite plants). The specific emissions improve by a further 1.1% when the USC replacements are added. System efficiency rises to 37.2% LHV, gross. The table also shows the effect of assuming that the USC replacements operate at a higher efficiency (47% LHV, gross for black coal, 46% for lignite). The system efficiency rises to 37.4% LHV, gross.

New lignite units could use fuel drying in the near future to further raise the efficiency. The effect of replacing or retrofitting all lignite capacity with USC units incorporating lignite drying, for a 50% LHV, gross efficiency, without any changes to the black coal capacity, was also examined. Table 23 shows that this measure alone could cut emissions by 21 Mt/y (11%).

7.5 2030 Baseline

7.5.1 Initial approach – existing capacity as baseline

Outputs from the model for this approach for the baseline of 2030 are shown in Table 24. The basis

Table 23 CO_2 emissions, generation and efficiency estimates in 2015, using system capacity factor of 73.4%, for Australia's coal-fired power plants, for baseline and different scenarios

	Baseline	Close subcritical commissioned before 1971	Close pre-1971 subcritical and replace instantaneously with USC at 44% LHV gross average efficiency	As previous column, assuming USC at 47% LHV gross average efficiency	All lignite plants replaced with 50% LHV, gross USC with fuel drying
CO_2, Mt	184	161/177*	175	174	163
TWh, gross	188	171/188*	188	188	188
CO_2 g/kWh, gross	976	942 (reduced by 3.5%)	931 (total reduction of 4.6%)	926 (total reduction of 5.1%)	866 (total reduction of 11%)
System efficiency, % LHV, gross	35.6	36.7	37.2	37.4	39.8

* Second values here assume other coal-fired units make up drop in generation from closures - see main text

here is for a rundown of capacity, so the power generated and associate emissions are lower than at the starting point in 2015. Capacity factor is kept at 73.4% throughout. For a 50-year plant retirement age, system efficiency is 36.3% LHV, gross. For a 60-year plant life, system efficiency is 35.6% LHV, gross. Figure 4 illustrates the strong influence of the assumed plant retirement age on generation from the surviving units in 2030.

A-USC and advanced IGCC technologies will be commercially available by 2030. The model has been used to assess the potential benefit from replacing all the subcritical capacity surviving at that time with these technologies, assuming efficiencies of 51% LHV, gross, for hard coal, 54% for A-USC with lignite drying for lignite, while keeping gross power generation constant. Table 24 shows that 30–50 Mt/y of CO_2 emissions would be saved, depending on surviving capacity for replacement (which depends in the model on the assumed plant retirement age).

Australia is also active in the field of CO_2 capture and storage (CCS), and the effect of the replacement plants incorporating CCS was also assessed. A further 60–90 Mt of CO_2 emissions would be saved, for the same generation.

The large dependence on lignite for power production in Victoria is driving interest in CCS particularly strongly there. The Government of Victoria and the Federal Government are financially supporting a project, CarbonNet, that, if progressed, would involve capturing 1–3 Mt/y of CO_2 from the Latrobe Valley lignite power plants and storage of the CO_2 in the Gippsland Basin, with potential scaling up (Department of Primary Industries, 2012). The saving in emissions by installing A-USC lignite plants with lignite drying, with and without CCS in place of the lignite systems in the Latrobe Valley that would still be there in 2030 is shown separately in Table 24. CO_2 emissions savings compared with the reference are 13 Mt/y without CCS and 30 Mt/y with CCS.

7.5.2 Including new plants

For the second assessment of the 2030 situation, plant replacements and new plants are assumed to be added between 2015 and 2030 to meet an estimated total capacity in 2030. The US EIA has estimated that coal consumption for power generation in Australia and New Zealand will remain fairly constant to 2035 as other sources of energy meet demand growth (EIA, 2011). Australia accounts for 96% of the two countries' coal consumption, and the assumption was therefore made that coal capacity would remain constant over the period, and the model capacity growth from 2015 was set to zero to achieve this. Capacity factor was kept at 73.4% throughout.

Table 24 CO_2 emissions, generation and efficiency estimates in 2030 for Australia's coal-fired power plants, for baseline of rundown of existing capacity

	Baseline 50 year life/ 60 year life	Replace all pre-2001 PCC units with A-USC or advanced IGCC at 51–54% LHV, gross efficiency; 50-year life/60-year life	As in previous column, but with replacement plants incorporating CCS; 50 year life/60-year life	Replace Latrobe plants with A-USC; 50 year life	Replace Latrobe plants with A-USC with CCS; 50 year life
CO_2, Mt	117/166	86/117	26/26	104	87
TWh, gross	122/171	122/171	122/171	122	122
CO_2 g/kWh, gross	956/971	704/687	213/152	852	711
System efficiency, % LHV, gross	36.3/35.6	49.1/50.2	49.1/50.2	40.4	40.4

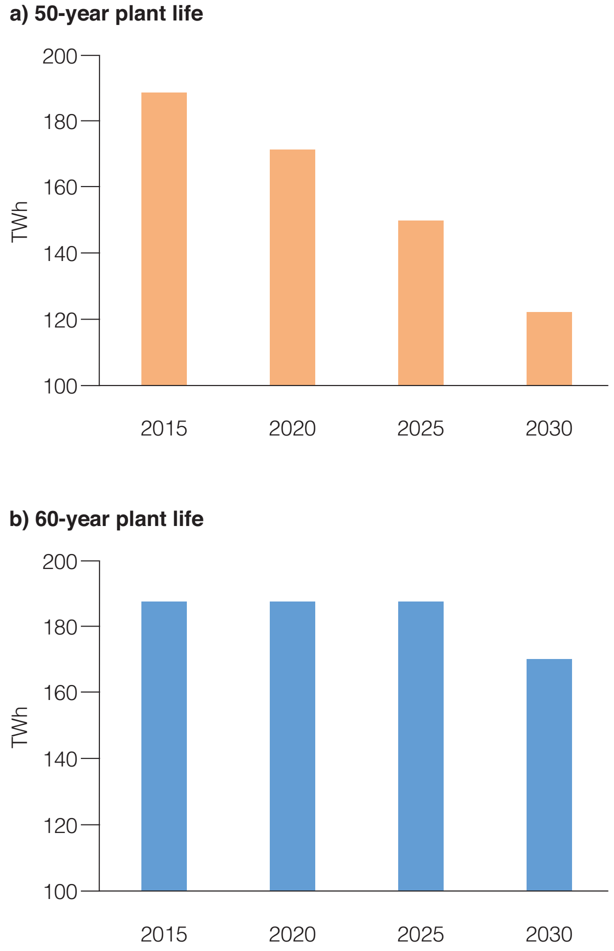

Figure 4 Effect of varying plant retirement age on calculated generation from existing capacity for Australia (TWh)

As for the other countries, two basic situations were compared. In the first, the model was set such that the replacement units resulted in the same proportion of subcritical plants being present in 2030 as in 2015. The efficiencies assumed for the SC and above plants were in this case 46% to 2020, 49% to 2025 and 51% to 2030, all LHV, gross, all with three percentage points higher for lignite, assuming fuel drying. In the other, all replacements added between 2015 and 2030 were assumed to be USC to A-USC (or IGCC), so no new subcritical units would be built. Table 25 shows the results. Generation increases, for both of plant retirement ages. Greater emissions reductions ensue if no subcritical plants are built, and CCS increases the benefit. Benefits are considerably greater for the earlier plant retirement age as there are more replacements of improved efficiency.

Table 25 CO_2 emissions, generation and efficiency estimates in 2030 for Australia's coal-fired power plants, for baseline of constant capacity to 2030

	Baseline (subcritical and supercritical new constructions after 2015) 50-year life/60-year life	All new constructions from 2016-2030 as USC, A-USC or IGCC 50-year life/60-year life	As in previous column, but with new plants incorporating CCS 50-year life/60-year life
CO_2, Mt	175/181	163/177	121/167
TWh, gross	188/188	188/188	188/188
CO_2 g/kWh, gross	930/965	867/944	645/888
System efficiency, % LHV, gross	37.3/35.9	40.0/36.7	40.0/36.7

8 UK

8.1 Current situation

The UK has about 30 GW of coal-fired capacity currently (2012). Of this, over 8 GW consists of 'opted out' plants under the EU LCPD regulations, and this capacity will close by the end of 2015, leaving about 21 GW, virtually all consisting of large units (500 MW or larger). Table 26 shows the plant tranches as determined for this work, with estimated efficiencies. All are subcritical, and all fire hard coal. Biomass is also being fired at up to about 15% (energy input) to enable the utilities to meet their renewable generation obligations. The coal-fired system provided 104 GWh (30% of the UK's electricity supply) in 2010, and the average capacity factor of the coal-fired system was 40.9% (Plant loads, demand and efficiency (DUKES 5.10) from DECC, 2011c). The opted-in units, which are fitted with FGD, have higher utilisations. For example, the 4 GW power plant at Drax, in the UK, operates at full load on all units in the daytime, reducing output at night, equivalent to an estimated annual utilisation of 85%. As well as adding FGD, the plants have had, or are in the process of having, turbine modernisation programmes. These developments mean that, although the generating stock is mostly quite old (around 40 years), they should be capable of continuing to be used for at least another ten years. As an example, at Drax, the site of the UK's first FGD installations, all the high pressure and low turbines are being replaced (Drax Power, 2011). The information in DECC (2011c), referred to above, shows that 288 GWh of fuel provided the 104 GWh of gross power from major power producers, corresponding to an efficiency of 36.1%, HHV, gross basis (equivalent to approximately 38%, LHV, gross).

The UK could likely have an IGCC plant incorporating CCS operating within a few years of 2015, and an oxy-coal system is also in prospect. The former is included in the 2030 estimates of emissions in Section 9.5.

8.2 Model calibration

To verify the model against 2009 data from IEA (2010) and provisional 2010 data from DECC (2011b,c), the opted-out units were temporarily included. Setting the coal-fired system capacity factor to the 40.9% referred to in the above paragraph gave estimated total generation for 2010 of 105 TWh. The DECC data in the Electricity from fuel use, generation and supply table, DUKES 5.6, in DECC (2011c) and IEA (2010) data showed 104–105 TWh. CO_2 emissions were calculated at 94 Mt. The CO_2 estimates assume that no biomass is fired. For comparison, the UK national greenhouse gas inventory provisional data for 2010 shows 101 Mt (DECC, 2011b), but that also includes coal used for other sectors as well as electricity production. These checks confirmed the model was capable of giving reasonable results, but it was then necessary to fix upon an appropriate system utilisation for the assessments.

Between 2008 and 2009, there was an increase in the proportion of electricity produced from nuclear that reduced both coal and natural gas generation. The total generation was also depressed by the economic recession (DECC, 2011a). This averaged 359 TWh between 2006 and 2008, but was 342 TWh in 2009. Between 2006 and 2008, the average capacity factor of the coal plants was 49.3% and generation averaged 132 TWh. The sharp decrease in coal generation in 2009 (to 99 TWh) was followed by an increase in 2010 to the 104 TWh. Total generation that year rose to 348 TWh. Thus, coal took up 5 TWh of the 6 TWh increase. By 2015, coal-fired generation will be from a considerably reduced capacity. It is likely that, as these units will all have FGD, they will be competing on an equal footing with each other, and a fixed utilisation has been assumed across these plants. In order to equal the generation achieved by the coal-fired system in 2010 (104 TWh), the capacity factor needed would be 56%. To obtain the average generation achieved by the coal-fired

Table 26 UK coal plants data				
Commissioning date	% efficiency LHV	MWe	% efficiency LHV	MWe
	Hard coal		Lignite	
SC and USC				
Up to 1970				
1971-1975				
1976-1980				
1981-1985				
1986-1990				
1991-1995				
1996-2000				
2001-2005				
2006-2010				
2011-2015				
TOTALS				
SUBCRITICAL				
Up to 1970	38	10438		
1971-1975	38	5940		
1976-1980	38	2160		
1981-1985	39	1710		
1986-1990	40	660		
1991-1995				
1996-2000				
2001-2005	34	393		
2006-2010				
2011-2015				
TOTALS		**21301**		
Efficiency basis: all LHV, gross, estimated annual average Situation in 2015; based on operating or believed under construction, less those expected to close before end 2015				

system between 2006 and 2008 (132 TWh), the capacity factor would need to be 71%. If the total generation for 2015 returns to the pre-recession average of 359 TWh, and coal again takes up most of the increase, the coal generation will rise by perhaps 9 TWh to 113 TWh. The capacity factor to achieve this in 2015 would be 60.5%. The latter has been used for the 2015 baseline and scenarios, while recognising that it is clearly very uncertain what the market share and so utilisation of these plants will amount to in practice.

8.3 Baseline CO_2 emissions (2015)

The basis of calibration was described in the previous section. The baseline emissions, generation and specific emissions for the 2015 baseline are shown in Table 27. The estimated emissions are 101 Mt, and the specific emissions are 895 gCO_2/kWh gross. The predicted average fleet efficiency in 2015 is 38.1% LHV, gross basis.

8.4 Scenarios from 2015 baseline

For 2015, as the long life subcritical units are already improved or in the process of being improved by turbine refurbishment, the potential improvement options in the medium term consist of retrofits at some of these plants to convert to new USC systems. Because these would effectively become new plants, it is clear from UK Government policy that a substantial proportion of CO_2 capture would need to be included. The effect of CCS is examined for new plants using the 2030 scenarios. The emissions savings from moving to USC conditions on all the current systems without CCS was evaluated for 2015. Table 27 shows that an overnight conversion to USC would save 14–19% of emissions, for the same quantity of power generated, depending on the assumptions. The system efficiency would rise to the assumed efficiencies for the USC conversions, as no plants are here left as they are.

8.5 2030 Baseline

8.5.1 Initial approach – existing capacity as baseline

Outputs from the model for this approach for the baseline of 2030 are shown in Table 28. The basis

Table 27 CO_2 emissions, generation and efficiency estimates in 2015, using system capacity factor of 60.5%, for the UK's coal-fired power plants, for baseline and different scenarios

	Baseline	Retrofit all units to become USC at 44% LHV gross average efficiency	As previous column, assuming USC at 47% LHV gross average efficiency
CO_2, Mt	101	87	82
TWh, gross	113	113	113
CO_2 g/kWh, gross	895	774 (reduced by 14%)	725 (total reduction of 19%)
System efficiency, % LHV, gross	38.1	44.0	47.0

Table 28 CO_2 emissions, generation and efficiency estimates in 2030 for UK coal-fired power plants, for baseline of rundown of existing capacity

	Baseline 50-year life/ 60 year life	Replace all pre-2001 PCC units with A-USC or advanced IGCC at 51 LHV, gross efficiency 50-year life/60-year life	As in previous column, but with replacement plants incorporating CCS 50-year life/60-year life
CO_2, Mt	14/53	11/40	3/6
TWh, gross	19/62	19/62	19/62
CO_2 g/kWh, gross	707/856	561/634	172/99
System efficiency, % LHV, gross	39.3/37.6	47.3/49.8	47.3/49.8

here is for a rundown of capacity, so the power generated and associate emissions are lower than at the starting point in 2015. The capacity factor was kept at 60.5%. For a 50-year plant retirement age, only a small capacity remains, and CO_2 emissions are 14 Mt/y. For a 60-year plant life, emissions are 53 Mt/y. Some new coal capacity will probably be built in any case by 2030 (although almost certainly with CCS from the outset because of Government policy). Section 8.5.2 examines this.

The model has been used to assess the potential benefit from replacing all the pre-2001 subcritical capacity surviving at that time (leaving a 2x195 MW subcritical plant re-opened in 2001) with A-USC and advanced IGCC technologies, assuming efficiencies of 51% LHV, gross, while keeping gross power generation constant. Table 28 shows that 3–13 Mt/y of CO_2 emissions would be saved, depending on surviving capacity for replacement (which depends in the model on the assumed plant retirement age).

The UK is actively interested in supporting large-scale CCS demonstrations (for example, the planned Don Valley IGCC plant in Yorkshire, which appears quite likely to be constructed, initially to be fuelled by natural gas, but within a further two years to be converted to IGCC). The model has been used to estimate the effect on emissions of incorporating CCS in the replacement A-USC or IGCC plants. Note that the Don Valley plant is assumed to be operating as CCS anyway, so none of the emissions difference between the two scenario columns in the table comes from that plant. A further 8–34 Mt/y of CO_2 emissions would be saved compared with no CCS on the replacement plants.

8.5.2 Including new plants

For the second assessment of the 2030 situation, plant replacements and new plants are assumed to be added between 2015 and 2030 to meet an estimated total capacity in 2030. For the purposes of this analysis, the assumption has been made that coal capacity remains constant over the period from 2015 to 2030. The model capacity growth was set to zero to achieve this. The capacity factor was kept at 60.5%.

As for the other countries, two basic situations were compared. In the first, the model was set such that the replacement units resulted in the same proportion of subcritical plants being present in 2030 as in 2015. The efficiencies assumed for the SC and above plants were in this case 46% to 2020, 49% to 2025 and 51% to 2030, all LHV, gross. In the other, all replacements added between 2015 and 2030 were assumed to be USC to A-USC (or IGCC), so no new subcritical units would be built. Table 29 shows the results. Generation increases greatly, compared with the situation for no new plants, for both of the plant retirement ages, because a large amount of capacity is very mature. Greater

Table 29 CO_2 emissions, generation and efficiency estimates in 2030 for UK coal-fired power plants, for baseline of constant capacity to 2030

	Baseline (subcritical and supercritical new constructions after 2015) 50-year life/60-year life	All new constructions from 2016-2030 as USC, A-USC or IGCC 50-year life/60-year life	As in previous column, but with new plants incorporating CCS 50-year life/60-year life
CO_2, Mt	99/100	85/90	21/57
TWh, gross	118/118	118/118	118/118
CO_2 g/kWh, gross	838/854	725/768	177/485
System efficiency, % LHV, gross	39.4/38.7	45.3/42.9	45.3/42.9

emissions reductions ensue if no subcritical plants are built. Construction of new subcritical plants is highly unlikely, anyway. Furthermore, the addition of CCS to all new coal-fired plants appears virtually certain by 2030 because of Government policy in the UK. Including CCS reduces the emissions to very low levels, especially when the earlier plant retirement age is assumed, as there are more replacements.

9 Summary and conclusions

CO_2 emissions for 2015 and 2030 have been calculated using models of coal-fired generating systems for three non-OECD countries (China, India and South Africa) and three OECD countries (USA, Australia and UK). These account for 70% of world coal-fired capacity. Information on these fleets was taken from Coal Power, the IEA Clean Coal Centre's database, together with other sources. Plants were grouped according to age, technology and basic fuel type then efficiencies were estimated for each group for each of the countries. The models were then used to assess the effect on CO_2 emissions of applying efficiency upgrading and new CCT strategies appropriate to the countries. CCTs included supercritical and ultra-supercritical PCC, A-USC (with 700ºC+ turbines), IGCC and CO_2 capture. In this report, capacities and generation are reported gross, that is before plant own power consumption is deducted. Efficiencies are reported on a lower heating value (LHV), gross power, basis.

Total emissions and emissions savings from improvements obviously vary between countries because of the different sizes of the fleets. Another source of variation is in the different extents to which plants are used in the countries. Rather than apply a constant utilisation (capacity factor), we have endeavoured to apply realistic capacity factors in estimating generation and emissions. Specific emissions (in gCO_2/kWh gross) and system efficiencies were also calculated to facilitate comparisons. This summary tabulates some of the results. The main text contains more information and results of other scenarios.

Table 30 shows the estimated emissions, estimated emissions after listed improvements (with savings in parentheses) and specific emissions for the year 2015. This year was selected in order to include plants currently under construction, or believed to be close to this at the time of report preparation. Note that all the tables in this chapter give results for a plant retirement age of 50 years, except where

Table 30 Summary of results for 2015

<table>
<tr><th>Country</th><th>Metric</th><th>Baseline</th><th>Close subcritical commis-sioned before 1971</th><th>Raise efficiency of subcritical 2% pts</th><th>Replace subcritical with USC</th><th>Notes</th></tr>
<tr><td rowspan="2">China</td><td>Mt</td><td>4192</td><td rowspan="2">NA</td><td>4066 (–126)</td><td>3580 (–612)</td><td rowspan="2">USC 47% LHV gross</td></tr>
<tr><td>g/kWh, gross</td><td>882</td><td>856</td><td>754</td></tr>
<tr><td rowspan="2">India</td><td>Mt</td><td>1315</td><td rowspan="2">NA</td><td>1258 (–57)</td><td>1070 (–245)</td><td rowspan="2">USC 44% LHV gross</td></tr>
<tr><td>g/kWh, gross</td><td>975</td><td>932</td><td>793</td></tr>
<tr><td rowspan="2">South Africa</td><td>Mt</td><td>277</td><td rowspan="2">NA</td><td>264 (–13)</td><td>227 (–50)</td><td rowspan="2">USC 45% LHV gross; 60-year plant retirements age</td></tr>
<tr><td>g/kWh, gross</td><td>935</td><td>892</td><td>765</td></tr>
<tr><td rowspan="2">USA</td><td>Mt</td><td>2093</td><td>1510 (–583)</td><td rowspan="2">NA</td><td>1937 (–156)</td><td rowspan="2">USC at 47% LHV gross replacing pre-1971 units only</td></tr>
<tr><td>g/kWh, gross</td><td>939</td><td>921</td><td>869</td></tr>
<tr><td rowspan="2">Australia</td><td>Mt</td><td>184</td><td>161 (–23)</td><td rowspan="2">NA</td><td>174 (–10)</td><td rowspan="2">USC at 47% LHV gross replacing pre-1971 units only</td></tr>
<tr><td>g/kWh, gross</td><td>976</td><td>942</td><td>926</td></tr>
<tr><td rowspan="2">UK</td><td>Mt</td><td>101</td><td rowspan="2">NA</td><td rowspan="2">NA</td><td>82 (–19)</td><td rowspan="2">USC 47% LHV gross</td></tr>
<tr><td>g/kWh, gross</td><td>895</td><td>725</td></tr>
<tr><td>Total</td><td>Mt</td><td>8162</td><td></td><td></td><td>7070 (–1092)</td><td></td></tr>
</table>

Table 31 Summary of results for 2030 for baseline of rundown of existing capacity

Country	Metric	Baseline	Replace all or most older PCC with A-USC or advanced IGCC	As previous column, but with replacement plants incorporating CCS	Notes
China	Mt	4291	3731 (–560)	2688 (further –1043)	
	g/kWh, gross	909	790	569	
India	Mt	1247	941 (–306)	367 (further –574)	
	g/kWh, gross	996	752	293	
South Africa	Mt	280	217 (–63)	68 (further –149)	60-year plant retirements age
	g/kWh, gross	934	724	226	
USA	Mt	648	494 (–154)	192 (further –302)	
	g/kWh, gross	940	717	278	
Australia	Mt	117	86 (–31)	26 (further –60)	
	g/kWh, gross	956	704	213	
UK	Mt	14	11 (–3)	3 (further –8)	
	g/kWh, gross	707	561	172	
Total	Mt	6597	5480 (–1117)	3344 (further –2136)	

Table 32 Summary of results for 2030 for baseline of new constructions between 2015 and 2030

Country	Metric	Baseline (subcritical and supercritical for new constructions after 2015)	All new constructions from 2015 as USC, A-USC or IGCC	As in previous column, but with new plants incorporating CCS	Notes
China	Mt	6252	5984(–268)	4461 (further –1523)	
	g/kWh, gross	877	840	626	
India	Mt	1664	1586 (–78)	1281 (further –305)	
	g/kWh, gross	975	929	750	
South Africa	Mt	443	416 (–27)	294 (further –122)	60-year plant retirements age
	g/kWh, gross	919	865	611	
USA	Mt	1924	1752 (–172)	758 (further –994)	constant capacity 2015-2030
	g/kWh, gross	863	786	340	
Australia	Mt	175	163 (–12)	121 (further –42)	constant capacity 2015-2030
	g/kWh, gross	930	867	645	
UK	Mt	99	85 (–14)	21 (further –64)	constant capacity 2015-2030
	g/kWh, gross	838	725	177	
Total	Mt	10557	9986 (–571)	6936 (further –3050)	

stated otherwise. For each country within a given table in this chapter, gross power is constant across baseline and scenarios. The total CO_2 emissions for the six countries in 2015 are estimated at 8.2 Gt. A total of up to 1.1 Gt would be saved by replacing subcritical plants by USC or modern IGCC plants. As these countries represent 70% of world coal power generation capacity, it can be expected that over 1.5 Gt could likely be saved globally in this way.

For 2030, we are looking at greater uncertainties in the sizes of fleets and how much they are likely to be used. It is however possible to envisage greater efficiency changes from introducing the new CCTs as advanced USC pulverised coal (A-USC, with 700ºC and hotter turbines) and advanced IGCC, with higher temperature gas turbines and other improvements, will then be commercially available. The 2030s are also expected to be the first decade of application of CCS to all new coal-fired power plants. The estimated effects of such developments on emissions are collected in Tables 31 and 32. The baselines for these differed in that the first looked at the surviving 2015 capacity only, while the second used information or assumptions for projected future capacity in 2030 to predict a plant replacements and additions programme up to that year, before applying variations. For the latter, subcritical new plants are included for the baseline, and for the scenarios only USC or better plants are assumed. The total CO_2 saving was highly dependent on the baseline assumptions, but 0.6–1.1 Gt could be saved in 2030 in these countries. CCS on the new plants would increase these savings to well over 3 Gt.

Some of the results for each country are summarised below:

China is already well on the way to modernising its coal-fired fleet. Its efficiency has probably already reached the performance of the OECD area. The large capacity, expected to be approaching 1000 GW by 2015, will nevertheless result in 4.2 Gt of CO_2 emissions in 2015. The predicted average fleet efficiency in 2015 is 38.6% LHV, gross basis, compared with 37.5% LHV, gross, for 2008 for the OECD area. However, China's system could be used more efficiently, as the system load is too evenly spread at present. Applying a merit order system could effect a 2.3% improvement in system specific CO_2 emissions. Assuming the current even load spread is retained, replacing overnight all of the subcritical units by USC units could reduce CO_2 emissions by 500 Mt/y or more. An improvement programme to raise the efficiency of all subcritical plants by two percentage points would reduce specific emissions by about 3%.

By 2030, advanced PCC (A-USC) and advanced IGCC plants will be commercially available, including systems supplied by Chinese manufacturers. Emissions in 2030 are estimated at 6.0 Gt if future expected growth in capacity uses USC, A-USC or advanced IGCC. If the new and replacement plants were to have CCS, 4.5 Gt would be emitted. Even without CCS, the new and replacement plants would be saving 270 Mt/y compared with a plant population structure identical to the present.

India's large fleet of coal-fired power plants (189 GW estimated from this work for 2015) is estimated to result in more than 1.3 Gt/y of CO_2 emissions by 2015. The emissions in relation to capacity are proportionally higher than for China largely because the system utilisation is much higher (77% compared with 55%). The predicted average fleet efficiency for 2015 is 35.1% LHV, gross basis, compared with 31.7% LHV, gross, in 2010, demonstrating the improvement that is occurring. India's coals and hot climate limit what can be achieved, so this progress is impressive. Over 20 GW of subcritical capacity is scheduled for renovation by 2017. The model showed that an associated two percentage point efficiency improvement could save 11 Mt/y of CO_2. The predicted saving in CO_2 emissions if all subcritical units were to be improved in efficiency by two percentage points was 57 Mt/y (4%). Overnight replacement of all the subcritical plants by supercritical or USC units, could save about 200 Mt/y or more of CO_2 for constant generation. Emissions in 2030 are estimated at 1.6 Gt if future expected growth in capacity uses only USC, A-USC or advanced IGCC. If the new and replacement plants were to have CCS, 1.3 Gt would be emitted. Even without CCS, the new and replacement plants would be saving about 80 Mt/y compared with a plant population structure identical to the present.

Most of **South Africa's** power stations are coal fired. A major build and return-to-service programme is occurring to meet the rapidly growing demand for power. As in India, low quality coals, a hot climate and a growing need to conserve water affect realisable efficiency levels. The CO_2 emissions in 2015 were calculated at 277 Mt/y and the predicted average fleet efficiency at 36.7% LHV, gross basis. The fleet efficiency for 2010 was 35.8% LHV, gross, and the increase will come from the ongoing addition of supercritical units. For the same amount of power generated, raising the efficiency of all of the subcritical units by two percentage points reduces CO_2 emissions in 2015 by 13 Mt. For the same capacity factors, if all were instantaneously replaced by supercritical units of efficiency 45% LHV, gross, emissions would be reduced by 50 Mt. Emissions in 2030 are estimated at 416 Mt if future expected growth in capacity uses only USC, A-USC or advanced IGCC. If the new and replacement plants were to have CCS, 294 Mt would be emitted. Without CCS, the new and replacement plants would be saving about 30 Mt/y compared with a mixed subcritical/supercritical build.

In the **USA**, total coal-fired capacity is also large, currently about 325 GW, with many subcritical and supercritical units. There are variations, but the average efficiency of the supercritical units is about 3–4 percentage points higher than the average for the subcritical units in the same age range. Most of the supercritical stock dates from before 1981, but since the mid-2000s some imported supercritical and USC units have been installed. Some subcritical units have been constructed up to the present. Assuming a system capacity factor of 76%, CO_2 emissions in 2015 are predicted at 2.09 Gt, from 335 GW of capacity. Estimated average fleet efficiency in 2015 is 36.4% LHV, gross basis, and the predicted specific emissions of CO_2 are 3.4% higher than expected for China. A number of plant retirements have been announced recently because of more demanding emissions requirements being uneconomic to meet. There is a large capacity of subcritical plants dating from before 1971, and the effect of an instantaneous closure of these was evaluated. It resulted in the specific emissions decreasing by 1.9%. Instantaneously replacing these plants with an equal capacity of state-of-the USC plants of 47% gross LHV operating efficiency would save over 150 Mt/y of emissions. Emissions in 2030 are estimated at 1.75 Gt if future expected growth in capacity uses only USC, A-USC or advanced IGCC. The new and replacement plants would be saving about 170 Mt/y compared with continuing to build some of them as subcritical. If the new and replacement advanced plants were to have CCS, another 1.0 Gt would be saved.

Most of **Australia**'s power stations are coal fired, including 26 GW of subcritical,7 GW of which are lignite fired. Much of the subcritical capacity is over 20 years old, and turbine upgrades to improve performance have been done or are in progress. The lignite plants in Victoria use a very low cost fuel but are mostly fairly old, and have high CO_2 emissions. Emissions in 2015 are estimated at 184 Mt. System efficiency is calculated at 35.6% LHV, gross. The effect of replacing all pre-1971 plants with USC units of efficiency 47% LHV gross would be to reduce total emissions by 10 Mt/y. Other options were also examined. Replacing or retrofitting all lignite capacity with USC units incorporating lignite drying, for a 50% LHV, gross efficiency, without any changes to the black coal capacity could cut emissions by 21 Mt/y. Emissions in 2030 are estimated at 163 Mt if capacity replacements use only USC, A-USC or advanced IGCC. This assumes that total coal-fired capacity in 2030 is the same as in 2015. The future advanced plants would be saving about 12 Mt/y compared with building some of them as subcritical. If the new and replacement advanced plants were to have CCS, another 42 Mt would be saved.

The **UK** has about 30 GW of hard coal fired capacity, all subcritical. Of this, over 8 GW consists of 'opted out' plants under the EU LCPD regulations, and these will close by the end of 2015, leaving 21 GW, and virtually all consisting of 500 MW units or larger. All have had or are having major works to improve their turbines and extend their life. The UK could likely have an IGCC plant incorporating CCS operating within a few years after 2015, and an oxy-coal unit is also in prospect. If the total generation for 2015 returns to the pre-recession average, and coal takes up most of the increase, the coal generation will be 113 TWh. Estimated emissions in 2015 are 101 Mt. The predicted average fleet efficiency in 2015 is 38.1% LHV, gross basis. A theoretical overnight conversion by retrofits to new USC at 47% LHV gross would reduce emissions to 82 Mt. However, USC units are more likely at sites of closing units. Emissions in 2030 are estimated at 85 Mt if future plants use only USC, A-USC or advanced IGCC. The future advanced plants would be saving about 14 Mt/y compared with continuing to build some of them as subcritical. If the new and replacement advanced plants were to have CCS, another 64 Mt would be saved.

The study clearly shows the large CO_2 emissions savings that could come from efficiency improvements at existing units or through plant replacements in all these countries. CCS is still some time away from routine commercial deployment, and the urgency of applying more widely the type of efficiency improvement programmes outlined here is increasing.

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