Upgrading the efficiency of the world's coal fleet to reduce CO_2 emissions

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, Canada, China, the European Commission, Germany, India, Italy, Japan, New Zealand, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

This study examines the role of HELE (high efficiency, low emission) coal-fired power plant in helping to meet the goal of reduced carbon dioxide emissions by setting out an overview of the prospects for the role of HELE technologies in a number of major coal user countries. Ten countries have been selected for study and are (in alphabetical order); Australia, China, Germany, India, Japan, Poland, Russia, South Africa, South Korea and the USA. The target countries have differing coal-plant fleet ages and efficiencies, and different local conditions and policies which impact on the scope for HELE implementation.

The profile of the coal fleet for each country has been calculated to meet future electricity demand under three scenarios with progressively greater replacement of lower efficiency capacity with HELE technology, and the consequent emissions of carbon dioxide and costs of implementation determined. The results are discussed in terms of potential carbon dioxide savings and the prospects for adopting a HELE upgrade pathway in the context of current energy policy.

Acronyms and abbreviations

ANRE	Agency for Natural Resources and Energy
AUSC	advanced ultra-supercritical
CCS	carbon capture and storage
CFBC	circulating fluidised bed combustion
DECC	Department of Energy and Climate Change
EIA	Energy Information Administration
ETS	Emissions Trading Scheme
FBC	fluidised bed combustion
GDP	gross domestic product
HELE	high efficiency, low emissions (coal plant)
HHV	higher heating value
IEA	International Energy Agency
IEO	International Energy Outlook
IGCC	integrated gasification combined cycle (plant)
IGFC	integrated coal gasification fuel cell combined cycle
LHV	lower heating value
METI	Ministry of Economy, Trade and Industry
NEDO	New Energy and Industrial Technology Development Organisation
OECD	Organisation for Economic Co-operation and Development
PCC	pulverised coal combustion
SUEK	Siberian Coal Energy Company
TPES	total primary energy supply
USC	ultra-supercritical
WEPP	World Electric Power Plants (database)

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Units used

Btu	British thermal unit
grammes/kWh	grammes per kilowatt hour
Gt	gigatonne
kW	kilowatt
kWh	kilowatt hour
Mt	million tonne
MWe	megawatt electrical
^{o}C	degrees Celsius
RMB	Renminbi
TWh	terawatt hour
US$	United States dollar

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1 Introduction

Coal remains an important source of energy for the world, particularly for power generation. During the last decade the demand for coal has grown rapidly, exceeding the demand for gas, oil, nuclear and renewable energy sources. Various projections for the future global growth in energy demand suggest that this trend is likely to continue, dominated by coal use in the emerging economies such as China and India. Continuing pressure on the need to cut emissions of carbon dioxide to mitigate the effects of climate change, and to limit the average rise in global temperature to between 2°C and 3°C, mean it will be necessary to halve (from current levels) carbon dioxide emissions by 2050. To contribute to this goal, emissions from coal-fired power generation will need to be reduced by around 90% over this period. In the IEA climate change 450 ppm carbon dioxide scenario, around 3400 large-scale CCS plants need to be operating globally by 2050 for the effective abatement of carbon dioxide emissions (IEA, 2012). At the same time the need for energy and its economic production and supply to the end-user need to remain central considerations in power plant construction and operation.

In 2012 the IEA (Paris) published an report 'Technology Roadmap – High-Efficiency, Low-Emissions Coal-Fired Power Generation' (IEA, 2012) which concluded that in general terms, larger, more efficient and hence younger coal plants are the most suitable for economic carbon capture and storage (CCS) retrofit but that this would currently only be possible on around 29% of the existing total installed global coal-fired power station fleet. The IEA reported that, on average, the efficiency of existing world coal-fired capacity is comparatively low, at about 33%, although the recent establishment of large tranches of modern plant particularly in China is raising this figure. This means that relatively large amounts of coal must be used to produce each unit of electricity. As coal consumption rises, so do the levels of CO_2 and other pollutants. Consequently it has been recognised that coal-fired plant operating at the highest efficiencies is the most appropriate option for CCS retrofit in order to gain the greatest reduction in carbon dioxide emissions per unit of electricity generated. Such plants are described by the acronym HELE which stands for high efficiency, low emission (plant). Figure 1 illustrates the impact of employing progressively more effective HELE technologies on carbon dioxide abatement.

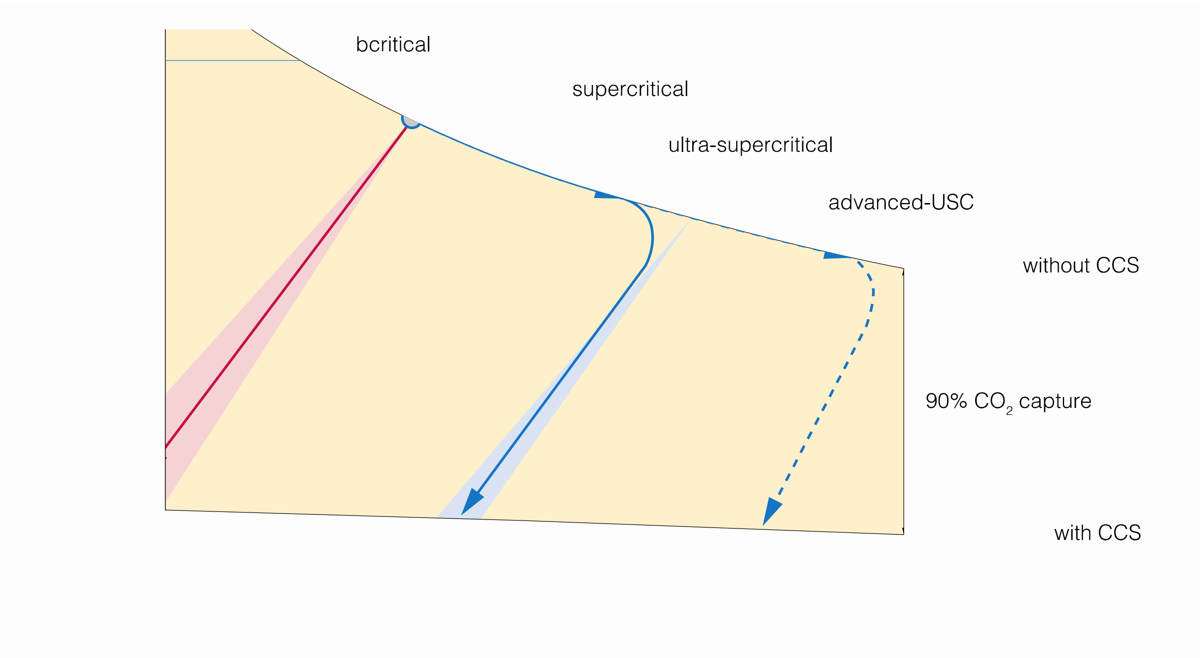

Figure 1 Reducing carbon dioxide emissions from pulverised coal fired power generation (IEA, 2012)

By way of illustrating the theoretical potential of HELE technologies, Figure 2 summaries the impact of different steam cycle conditions on an 800 MWe power station boiler burning hard coal and operating at a capacity factor of 80%. The unit will generate 6TWh electricity annually and emit the following quantities of carbon dioxide, depending on its steam cycle conditions and corresponding efficiency.

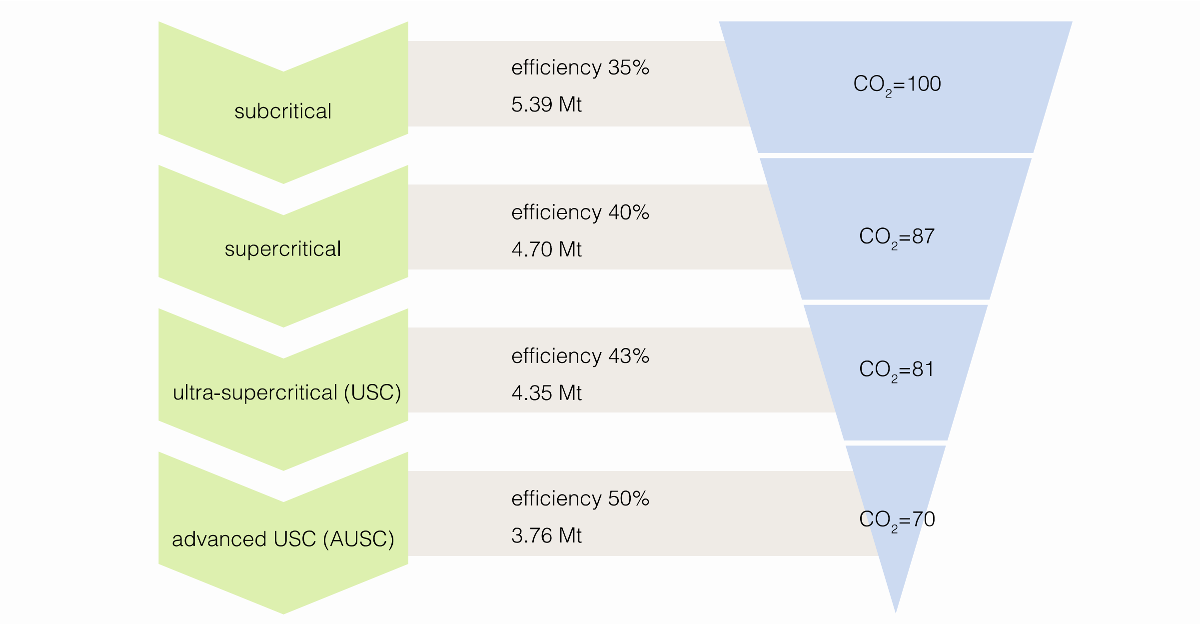

Figure 2 The impact of HELE technologies on emissions of carbon dioxide

Thus, replacing a unit of this type operating with a subcritical steam cycle with a unit based on advanced ultra-supercritical technology (under development) would result in savings of carbon dioxide in the region of 30%. The benefits of implementing HELE technologies worldwide was further underlined by the World Coal Association's calculation of savings of 2.25 Gt carbon dioxide annually if all of the coal-fired power plants (with an average reported operating efficiency of 33%) were upgraded or replaced with state-of-the-art HELE units operating at an efficiency of 45%. This figure is greater than the current total carbon dioxide emissions of India, and corresponds to approximately 19% of the total annual emissions from the power sector (World Coal Association, 2013).

This study examines the role of HELE coal in helping to meet the goal of reduced carbon dioxide emissions by setting out an overview of the prospects for the role of HELE technologies in a number of major coal user countries. Ten countries have been selected for study and are (in alphabetical order); Australia, China, Germany, India, Japan, Poland, Russia, South Africa, South Korea and the USA. The target countries have differing coal-plant fleet ages and efficiencies, and different local conditions and policies which impact on the scope for HELE implementation.

While the scope of this study using a methodology developed with, and based on, published validated data is valuable in setting out the potential for HELE technologies in carbon dioxide abatement in different countries, it is recognised that this needs to be followed-up by deeper analysis. The present study is considered to be a gateway document leading to a series of individual country studies similar to the IEA CCC 'Clean coal prospects in…' series where country-specific factors are considered in detail, and the views of major stakeholders within each country incorporated, to give a comprehensive view on HELE implementation pathways as part of the local energy, economic and environmental landscape. Furthermore, other important developing coal producing and using regions (eg the Asian Tiger Economies) should be incorporated within the enlarged HELE pathways series to ensure a comprehensive representation of global coal-sourced emitters of carbon dioxide.

2 Background and methodology

2.1 Study methodology

The study was undertaken using the methodology outlined in Figure 3 below and detailed thereafter.

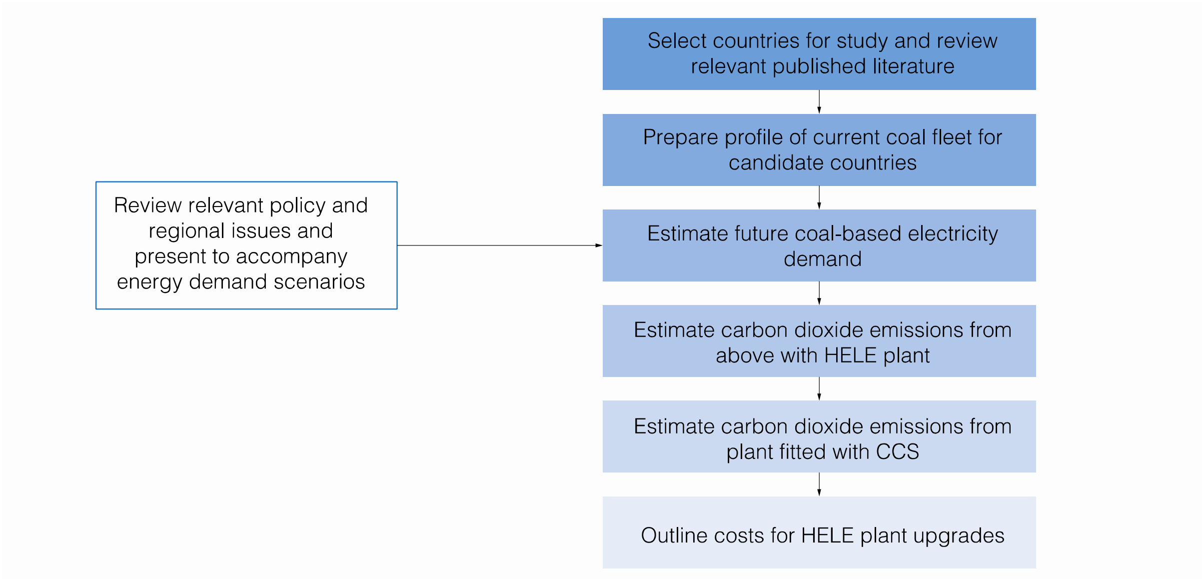

Figure 3 Methodology for study

2.1.1 Selection of countries

The ten countries that have been selected for study currently account for more than 85% of global carbon dioxide emissions arising from the use of coal (all types) for power generation and emitted over 7 Gt of the greenhouse gas in 2010 (IEA, 2010). The countries represent a range of economies from developed to developing, with differing coal fleet profiles, growth prospects and regional policies. Wherever possible, if a country has published a detailed energy plan that encompasses the role of HELE coal plant, this is reviewed and summarised in the relevant section. Where a plan is considered significantly out of date, published information is reviewed, précised and presented.

2.1.2 Profiling individual coal fleets

Data on coal-fired power generation units were abstracted from the UDI World Electric Power Plants Database (WEPP) in order to prepare a profile of each country's coal fleet, setting out the installed capacity as a function of age grouped by date of commissioning and steam cycle technology. The collated data sets are presented in tabular and graphical format. The WEPP is a global inventory of electric power generating units (Platts, 2013) and contains design data for plants of all sizes and technologies operated by regulated utilities, private power companies, and industrial autoproducers (captive power). It has been licensed by the Clean Coal Centre and the base dataset interrogated for the study contains up-to-date information for plants in operation, under construction, or planned as of 2013. WEPP reporting of power plant data is comprehensive, and widely used, but it should be pointed out that it is not regarded as a definitive catalogue of coal-fired power plant. Platt's claim over 95% coverage of individual countries coal fleets with the exception of China where a figure of 75% coverage is claimed. This is a consequence of the incredibly rapid transformation of China's power sector where it is reported that more than four new power plants are being built every week (Galuszka, 2012). Concomitant with this new build is the programme of 'Large Substitutes for Small (LSS)' (Mao, 2012) where 76830 MWe small power plant units capacity were decommissioned during the '11th Five-Year Plan' and over 200,000 MWe high efficiency larger units installed by 2010. There remain some 100000 MWe of inefficient small/medium capacity plant (approximately 12% of total capacity) including a number of units in the size range of 200–300 MWe which will be decommissioned over the next few years and replaced with larger more efficient plant.

Coal-fired plant planned or under construction post-2013 is highlighted with its own entry in each profile. For some countries with a rapidly evolving coal fleet (eg China) there was some uncertainty over plant reported in the period 2010–13 where units 'under construction' are likely to be producing power. The dataset has been updated and cross-checked to minimise incorrect reporting of plant.

Pulverised coal combustion (PCC) is the world's dominant coal-based power generation technology and is likely to remain so for the foreseeable future. Increasingly advanced cycles have improved the efficiency of electricity PCC generation and research into advanced materials and steam cycle conditions promised to maintain this trend. The study therefore concentrates on PCC plant with high efficiency. Developments to PCC-based generation such as oxy-combustion may have a part to play in future CCS scenarios, but they are not considered sufficiently proven for inclusion at this stage. Alternatives to PCC such as integrated gasification combined cycle plant (IGCC) are also possible contributors to future generation sets, but specifiers consider their relatively small unit size and complexity currently make them less attractive economically than 'conventional' PCC plant.

Coal types from anthracite to lignite are utilised for power generation and each type has specific requirements for its efficient combustion. In addition, the primary coal characteristics such as energy content, water and ash content can vary; sometime widely. Since the main HELE technologies concern developments to the steam cycle, and these are applicable to the range of coal-burning units predictions of future coal use group these coal types together. That said, given the relative importance of lignite-based power generation to certain countries (eg Germany) some additional commentary and analysis is included where appropriate.

Despite concerted effort over many years at standardisation, the reporting of power plant efficiencies is still an area fraught with difficulty (CIAB, 2010). Plant operators may regard the information as being commercially sensitive and decline to share it; operators may not specify the split between electricity and heating markets where combined heat and power plant is in use; values may not specify if they are gross or net of on-site power use (typically 5% to 7% of gross power); reported figures may be design values that do not reflect the likely decline in efficiency over time; the basis for reporting may not be clear. In particular, the latter can cause problems where values are quoted without specifying if the calculation is based on higher heating value (HHV), or lower heating value (LHV). Lower heating values do not account for the latent heat of water in the products of combustion. For coal-fired power generation, efficiencies based on HHV are generally around 2% to 3% points lower than those based on LHV. In this study, all efficiencies are quoted on an HHV basis unless otherwise indicated.

Consequently, researchers have developed methodologies for estimating plant efficiencies. These can range from 'knowledgeable estimates' by workers with a significant experience in the power generation sector, to techniques that group plants into similar tranches based on criteria such as steam conditions. The latter approach is generally agreed to be the best technique to use in the absence of highly detailed reliable plant data, although the caveats outlined above may still apply regarding the input data used for calculation (Tam and Remme, 2013). Barnes and others (2007) developed a methodology to estimate coal-fire power unit efficiencies based on steam cycle conditions, with correcting factors for specific issues that are known to affect efficiency. It is described in Annex One. This methodology has been used to estimate efficiencies for tranches of power plant units grouped by age and technology. As a cross-check the values have been compared to the more in-depth estimates produced by Henderson and Baruya (2012) in their analysis of carbon dioxide reduction through improved efficiency plant and other published information (eg by VGB) the estimates revised if necessary.

2.1.3 Reviewing regional energy policy, growth prospects and related issues

While it is possible to prepare estimates of the relative contribution of coal to an individual country's possible future energy demands, it is important to consider these within the context of relevant regional issues. For example, for any given country there may be a presumption in favour of future coal generation, or conversely a presumption against it. National energy policy may set out targets for the size of the energy sector and coal's place within it. With the transfer of former state assets into private hands in recent years, the decision to build new coal capacity may lie outside government control and this can skew the composition of projected coal fleet sizes; the section on Australian prospects set out a good example of this. A preliminary review of projected energy scenarios published during the last five years for different countries quickly revealed a difficulty in presenting a scenario that could be viewed as stable enough to allow predictions of the forty year timescale of the analysis 'shifting sands'. That said, it is acknowledged that it is important to consider the results of the analysis in the context of current thinking on energy matters and so the future coal generation projections are accompanied with commentary relevant to each country to establish 'direction of travel'. A more comprehensive treatment of these issues is one of the aims of the deeper counter-by-country analyses outlined above.

2.1.4 Estimating future coal-based electricity demand

The macroeconomic analysis selected as the basis for the study is that for predicted growth in coal use for electricity generation by the US Energy Information Administration Energy Outlook 2013, reference case (baseline world economic growth of 3.6% per year from 2010 to 2040; Brent crude oil prices growing to US$163 by 2040). The IEO2013 Reference case projections do not incorporate assumptions about future policies and regulations related to limiting or reducing greenhouse gas emissions, such as caps or taxes on carbon dioxide emissions. The Reference case does, however, incorporate elements of existing regulations and national energy policies, such as the European Union's 20-20-20 plan and its member states' nuclear policies; China's wind capacity targets; and India's National Solar Mission. However, it is important to remember that any new and unanticipated government policies or legislation aimed at limiting or reducing greenhouse gas emissions could substantially change the trajectories of fossil and non-fossil fuel consumption presented in this outlook.

2.1.5 Estimating carbon dioxide emissions from projected coal fleet under different scenarios: base case, 50-year plant retirement and 25-year plant retirement

Three coal-based generation scenarios have been selected as the basis for this study:

Base case

For each country's coal fleet a base case was set out where the installed capacity operating at industry normal capacity factors was compared with the predicted coal-based electricity demand. Capacity factors of 70, 85, and 90 % are assigned initially, and any surplus or shortfall in generation is met by changes in capacity factor, utilising plant in the order: ultra-supercritical > supercritical > subcritical. Where there is an overall capacity shortfall, such as in the rapidly developing economies of China and India, ultra-supercritical plant is installed (overnight) to meet the higher demand. No plant retirements are modelled in this scenario. Plants are assigned the country-specific efficiencies as set out in Table 1. These have been estimated as described earlier and reflect the local conditions to a degree commensurate with other data in this overview; for example new higher efficiency coal fleets in the developing economies such as China, relatively old and inefficient Russian plant, and (Indian) plants burning high ash coals. For each operating tranche, the corresponding carbon dioxide emissions are calculated using efficiency-related factors for hard coals as set out in Table 2 (VGB, 2008) over the period 2015-40, at five yearly intervals. All plant operating at the outset is assumed to continue to generate and no allowance is made for efficiency reductions from plant ageing, or efficiency improvements from technical developments implemented during routine outages.

Table 1 Assigned plant efficiencies by steam conditions and country (based on VGB, 2008)

	Australia	China	Germany	India	Japan	Poland	Russia	South Africa	South Korea	USA
Subcritical	32	36	31*	28	35	30	26	33	36	33
Supercritical	40	40	40	38	40	40	30	38	40	38
Ultra-supercritical	43	43	43	43	43	43	43	43	43	43
AUSC	50	50	50	50	50	50	50	50	50	50

*Note. * Relative low value reflects significant lignite-fired capacity in coal fleet*

Table 2 Emissions factors for carbon dioxide arisings as a function of plant efficiency (based on VGB, 2008)

Efficiency	26	27	28	29	30	31	32	33	34	35	36	37	38
CO_2 (g/kWh)	1252	1215	1180	1145	1112	1079	1048	1018	988	960	933	908	883
Efficiency	39	40	41	42	43	44	45	46	47	48	49	50	
CO_2 (g/kWh)	859	837	815	795	775	757	740	724	709	695	682	670	

2.1.6 50-year plant retirement

The second scenario is based on the planned retirement of capacity at three review points; 2020, 2030 and 2040. Current practice in many OECD countries is to operate plant for approximately 40 years, and in some cases plants may be significantly older than this (Power Engineering 2012). Consequently, for this study a planned life of fifty years has been assigned and any plant older than fifty years at the review point is retired and replaced with ultra-supercritical units and the corresponding carbon dioxide emissions from the coal fleet are calculated. This scenario, together with the base case is used to estimate the cost of carbon dioxide reduction through HELE upgrades and CCS retrofit.

2.1.7 25-year plant retirement

A third case, 25-year plant retirement, reflects evolving practice in developing economies such as China to decommissioning plant (Minchener, 2014). As in the 50-year plant retirement scenario, the coal fleet profile is reviewed in 2020, 2030 and 2040, and plant older than twenty five years is retired and replaced with ultra-supercritical units in the 2020 review. For the 2030 and 2040 reviews, replacement plant is based on AUSC units, assumed to be commercially available after 2025. Again, the corresponding carbon dioxide emissions from the revised coal fleet are calculated. Given that the costs of AUSC-based plants are not well quantified at the present time, no cost calculations have been undertaken for this HELE variant.

A screenshot of an example spreadsheet for the calculations is shown below in Figure 4.

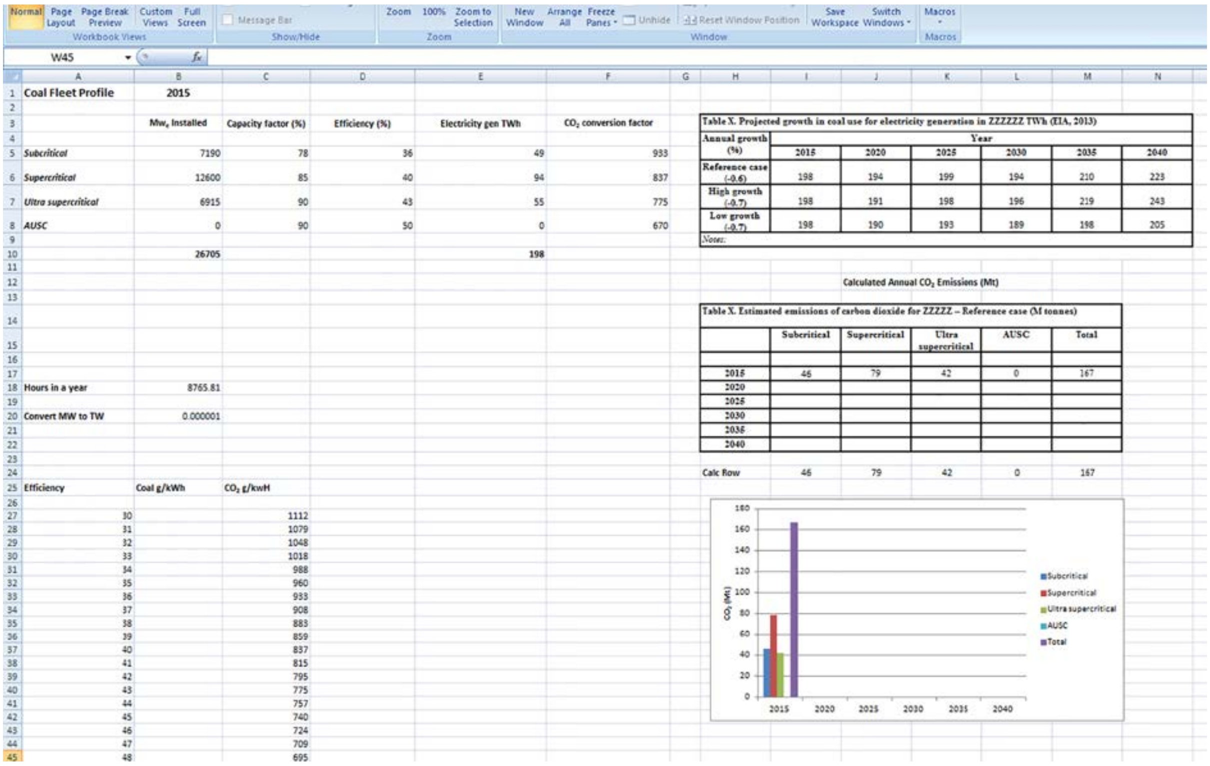

Figure 4 Extract of an example spreadsheet for calculation of required capacity to meet predicted demand and concomitant carbon dioxide emissions (South Korean base case 2015)

The results from the modelling exercise for each scenario are displayed in the form shown in Figure 5 below. Over the review period 2015-40 the projected coal based electricity demand is plotted (blue line) and the composition of the coal fleet determined according to the requirements of each of the three scenarios. The calculated carbon dioxide emissions from the coal fleet at each review point are plotted (red line), together with the composition of the fleet by steam cycle conditions (subcritical – green, supercritical – purple, ultra-supercritical – blue and AUSC (25-year plant retirement scenario only) – orange. A third trend line – dashed red, sets out the emissions of carbon dioxide that would follow from the fitment of CCS according to the assumptions set out later in this report. It should be noted that the additional capacity required by the plant derate that accompanies the operation of CCS is not included, or shown in this graphic; neither is the additional carbon dioxide that would be associated with that capacity. The dotted red line for CCS-carbon dioxide should therefore be regarded as a trend line.

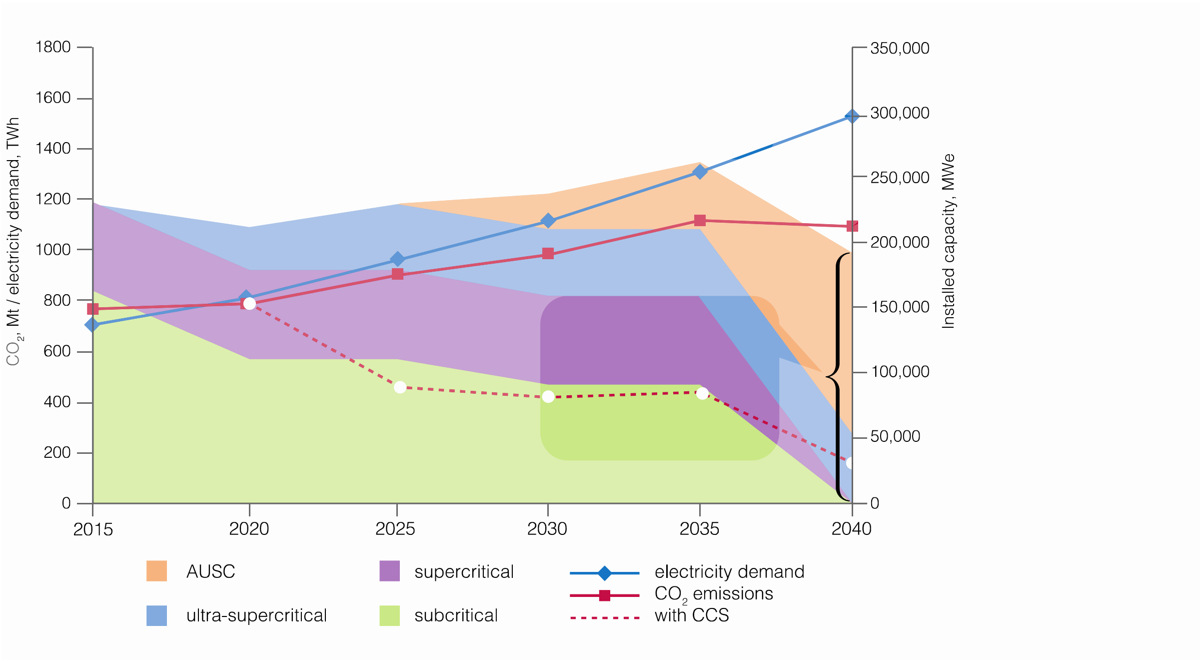

Figure 5 Example presentation of study results (India, 25-year plant retirement scenario) outlining the costs for HELE plant upgrades in candidate countries

The costs of plant construction and operation are usually subject to conditions of commercial confidentiality which makes site-specific detailed information difficult to obtain. However, several studies have been published by engineer-architect consultancies that relate to power generation plant that enable cost data to be recovered sufficient for use in this analysis. Presently, there is a large disparity between the cost of building plant in a developing country such as China, and an OECD country but this gap is closing as the forces of globalisation 'even up' many of the contributing factors. The IEA opine (Tamm, 2013) that the costs of building plant will converge sometime around 2030 and this is used as an assumption for relevant models. For the purposes of the overview study, and to facilitate comparisons, costs are therefore presented on a common basis as detailed in the relevant section below.

2.2 HELE technologies

HELE technologies for coal-fired power generation may be considered as falling into two main areas; improvements to pulverised coal (PC) firing based plant (the dominant technology), and advanced coal utilisation technologies, such as circulating fluidised bed combustion and integrated gasification combined cycle plant. These technologies have been reviewed and discussed extensively by, for example, Henderson (2013), Nicol (2013), Zhu (2013), Barnes (2013, 2011) and Henderson and Mills (2009), but a brief overview in the current study is useful in contextualising the present study.

2.2.1 Developments in pulverised coal firing plant

The HELE technologies applicable to PC-firing plant centre on improvements to the steam cycle allowing for steam higher temperatures and pressures and a consequent improvement in steam cycle efficiency. Historically, the majority of PC-fired plant was based on subcritical steam cycle technology, but with improvements in boiler tube materials, supercritical and ultra-supercritical steam cycles are now considered to be state-of-the-art. The definition of supercritical and ultra-supercritical boiler pressure and temperature conditions differs from one country to another, particularly the usage of the term ultra-supercritical, but the ranges cited by Nalbandian (2008) and shown in Table 3 are used frequently. A switch from subcritical to current ultra-supercritical steam conditions would raise efficiency by around 4 to 6 percentage points.

Table 3 Approximate pressure and temperature ranges for subcritical, supercritical and ultra-supercritical pulverised coal power plant (Nalbandian, 2008)

Pulverised coal power plant	Main steam pressure, MPa	Main steam temperature, °C	Reheat steam temperature, °C	Efficiency, %, net, HHV basis (inland, bituminous coal)
Subcritical	<22.1	Up to 565	Up to 565	33–39
Supercritical	22.1–25	540–580	540–580	38–42
Ultra-supercritical	>25	>580	>580	>42

Supercritical technology is already used in a number of countries and has become the norm for new plants in industrialised countries. Supercritical plants are currently located in eighteen countries, where their share in coal-fired power generation in those countries varies as shown in the analysis of individual country coal fleets in Section 3.

The first generation of supercritical units was relatively small compared to their subcritical predecessors and typically less than 400 MWe in size, but now larger units of up to 1100 MWe are being built based on ultra-supercritical technology (eg the Neurath, ultra-supercritical lignite-fired plant in Germany) and larger units are planned. The unit size of PCC plant has been steadily increasing and now 1000 MW units can be considered the norm for new installations. With the advent of 1300 MW units (eg at the Lianyungang, Jiangsu Province China complex) this upwards trend is set to continue.

Estimates suggest that ultra-supercritical plants could reduce fuel consumption and emissions by 25% to 30% compared to the best subcritical cycle based plants (Dalton, 2006).

The use of advanced materials means that boiler and steam turbine costs can be as much as 40% to 50% higher for an ultra-supercritical plant as compared with a subcritical plant (Burnard and Bhattacharya, 2011). However, these increased costs are partially offset by the balance of plant cost which can be 13% to 16% lower, owing to reductions in coal consumption, coal handling and flue gas handling. The total investment cost for ultra-supercritical plants can be 12% to 15% higher than the cost of a subcritical steam cycle. These issues are discussed in more detail in Section 4.2.

Looking further ahead advanced ultra-supercritical cycles (AUSC) otherwise known as 700°C technology, are under development. The status of advanced ultra-supercritical HELE technologies has been reviewed recently by Nicol (2013) and can be summarised as follows. Advanced ultra-supercritical is a term used to designate a coal-fired power plant design with the inlet steam temperature to the turbine at 700°C to 760°C. Average metal temperatures of the final superheater and final reheater could be higher, at up to about 815°C. Nickel-based alloy materials are thus required to meet this demanding requirement and industry support associations and private companies in the United States, European Union, India, China and Japan, have established programs for materials development and are working to develop this technology. If successful a commercial AUSC-based plant would be expected to achieve efficiencies in the range 45–52% (LHV (net), hard coal). Figure 6 sets out the AUSC material research programme timelines for major initiatives. Commercial AUSC plant could be widely available as soon as 2025, with the first units coming on stream in the near future (Coal Association of New Zealand, 2011).

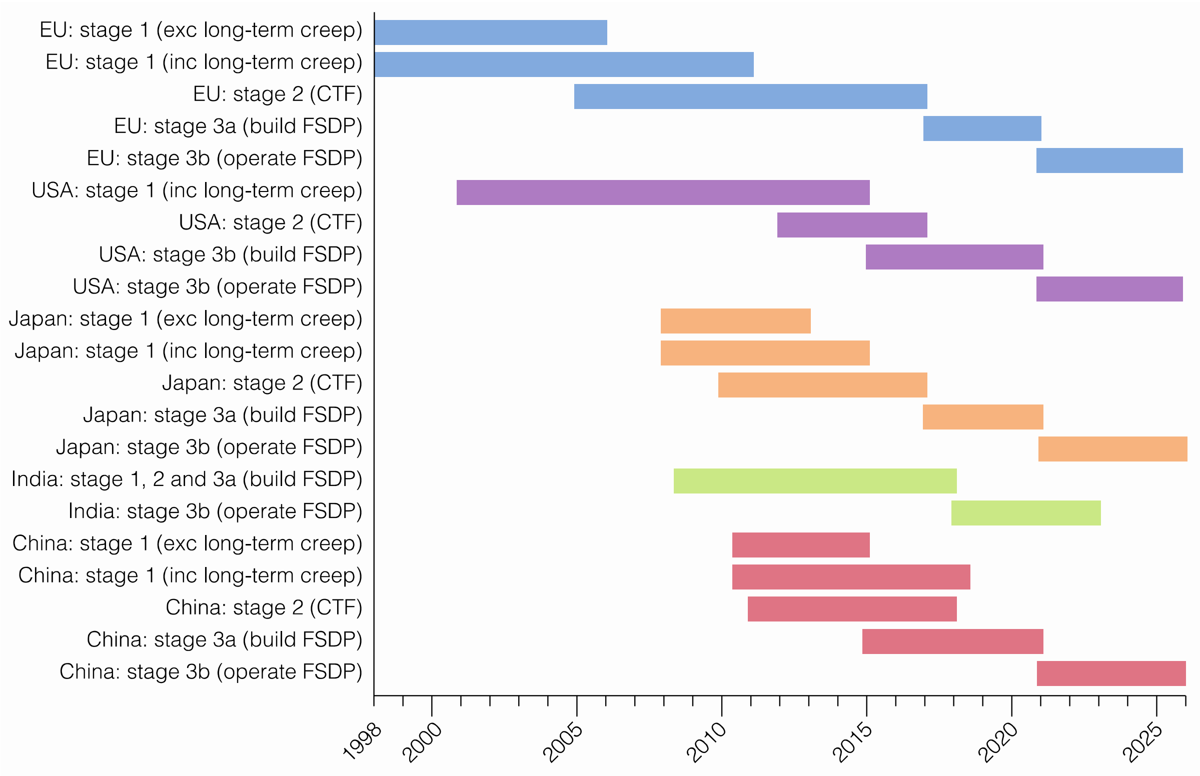

Figure 6 Development progress in major AUSC materials research programmes (Nicol, 2013)

However, there are still considerable uncertainties on the costs of AUSC–based plants and their cost-effectiveness ie does improved efficiency warrant the likely additional capital cost? Mao (2012) presented cost comparisons for USC and potential AUSC plants. In 2012 in China, the capital cost for a 600°C 2 x 1000 MW USC plant with single reheat is 8 billion RMB (1.23 billion US$), in which the cost of boiler tubing is 300 million RMB (46 million US$). However, for a 700°C 2 x 1000 MW AUSC plant with double reheat, the cost for boiler tubing *alone* will be at least 2.5 billion RMB (0.38 billion US$). Mao opined that the high cost of the high temperature steam tubing could be a bottleneck to restrict the use of 700°C AUSC plant. The projected increase of 5% efficiency was not considered sufficient to compensate for the cost of the high temperature materials, which could be restrict deployment of 700°C AUSC plant. Estimates of plants based on AUSC vary widely and without a commercial-scale demonstration unit, cannot be improved upon. As a primary aim of this study is to produce comparative cost implication for different HELE technologies, it has been decided to limit the HELE steam cycles to ultra-supercritical based plant.

Although PCC is by far the most commonly employed technology used in power generation from coal, two other technologies warrant discussion – Circulating fluidised bed combustion plant (CFBC) and Integrated gasification combined cycle plant (IGCC).

2.2.2 Circulating fluidised bed combustion plant (CFBC)

Circulating fluidised bed combustion plant have evolved from earlier bubbling bed fluidised bed combustion (FBC) technology where, primary combustion air is injected from beneath a bed of fuel suspending the particles and giving them fluid-like flow properties. In bubbling fluidised beds (BFB) low fluidising air velocities are employed to prevent fine particles from being carried out of the bed, but circulating fluidised beds use higher fluidising air velocities which entrain particles throughout the boiler. The flue gases are fed into solid separators (typically cyclones) that return solid bed and ash to the lowest part of the combustor and thus prevent unburnt fuel from leaving the furnace (*see* Figure 7). This creates a recycle loop through which fuel particles can pass 10 to 50 times until complete combustion is achieved. The prolonged combustion time results in much lower temperatures (800–900°C) than those found in PCC.

CFBC plants are particularly well suited to burning low grade coals or mixtures of coal with other fuels. As with PCC, the unit size has been steadily increasing with 600 to 800 MW supercritical CFBC commercially available and larger units under development. Notable CFBC installations include the supercritical high efficiency 460 MW CFBC unit in Łagisza, Poland and in China utility CFBC even at subcritical conditions has managed to capture a significant share of the country's rapidly growing coal capacity, and the recent commissioning of the world's largest supercritical CFBC unit may mark the beginning of similar growth at this scale.

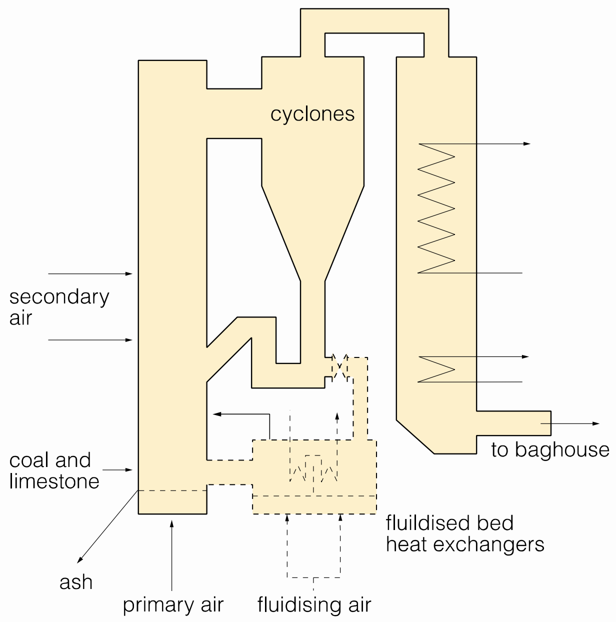

Figure 7 General schematic of a circulating fluidised bed boiler (Lockwood, 2013)

2.2.3 Integrated gasification combined cycle plant (IGCC)

IGCC plant gasifies coal in the presence of a sub-stoichiometric level of oxygen or air, to yield a gaseous fuel. A generalised schematic of an IGCC plant is given in Figure 8. IGCC plants utilising the latest generation of gas turbines that allow inlet temperatures of up to 1500°C can achieve cycle efficiencies higher than 45% (LHV, net). These are comparable with the efficiencies achieved by A–USC systems utilising pulverised bituminous coal.

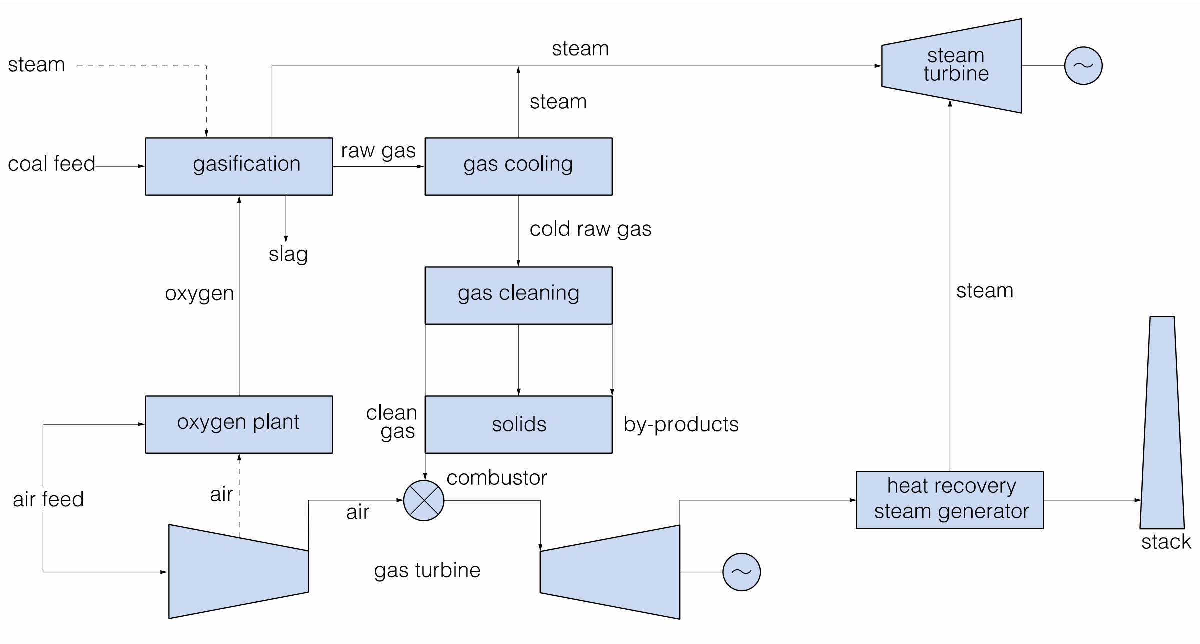

Figure 8 Integrated gasification combined cycle without carbon dioxide capture – major component systems (Henderson, 2008)

IGCC plant has inherently low emissions by design since the gaseous fuel is cleaned before it is fired in the cycle gas turbine. A number of developments and improvements to IGCC plants are underway (Barnes, 2011) and, for example, the introduction of 1700°C-class gas turbines could bring carbon dioxide emissions from IGCC below 670 g/kWh. A number of IGCC plants are under development worldwide and may have a role to play in contributing to HELE generation (Barnes, 2013). However, compared to PC plants, IGCC plants have higher capital and operating costs for power generation: higher redundancies are applied to mitigate risks, and there are a larger number of sub-systems and a need to contend with aggressive conditions in the gasifier. The fact that the size of the gas turbine constrains the unit size has also limited current market deployment of IGCC.

2.2.4 Efficiency improvements to lignite-fired plant

The high moisture content of lignite (up to 60%) is a major issue in its use in power generation. Zhu (2012) has recently reviewed developments in this area that may lead to improved efficiencies. When pulverised lignite is burned in a power plant, a significant amount of the energy in the coal is absorbed as heat to evaporate the water present before any useful energy can be obtained and converted to electricity. This leads to low thermal efficiency, high carbon dioxide emissions per unit of energy output and high capital costs of a plant. Other technical difficulties that arise from high moisture content include fuel handling problems, difficulty in achieving ignition, and larger boiler size required due to the increased flue gas volumetric flow. Therefore, drying of coal prior to combustion is important to improve thermal efficiency and consequently reduce carbon dioxide emissions. Extensive research and investigations have been carried out worldwide to develop energy efficient and cost effective coal drying processes. A number of approaches are taken to dry lignite and other low rank coals. These technologies broadly fall into two categories: evaporative drying and non-evaporative dewatering processes. Recently, several advanced coal drying technologies have been developed and are offered to the commercial market, whilst many more are under development. Among these, the WTA developed by RWE, Germany (Klutz and others, 2010) and the DryFining™ developed in the USA by a team led by Great River Energy (GRE, 2013), have been successfully demonstrated on commercial-scale lignite-fired power generating units. This is an area that is developing rapidly.

Lignite is a particular issue for Germany where it is usually used for electricity generation at, or near, the production site. In 2010, 91% of German lignite was used for electricity and heat generation, with the other 9% being used in patent fuel plants and production. German lignite production dropped from 357.5 Mt in 1980 to 176.5 Mt in 2011, a decrease of more than 50%. However, the country remains the world's leading lignite producer.

Finally, it is also possible to improve the efficiency of PC plant through minor modifications and the implementation of an effective operating routine. Many PC plant operators in OECD countries and in China have developed methods of offsetting the inevitable decline in plant efficiency from the 'newly commissioned' datum and have even increased the efficiency of long-established plant through the careful study and improvement of that plant (Npower, 2011). Most recently, some very impressive gains have been realised at the Shanghai Waigaoqiao No 3 power plant which comprises of 2 x 1 GWe ultra-supercritical coal fired units. The plant had a design net efficiency of 42% (LHV basis), but through a series of process optimisations and technological innovations the plant has been uprated to an annual net efficiency of 44.5% together with significant improvements in the plant's environments performance (Minchener, 2013). This approach is an attractive relatively low cost route to lowering carbon dioxide emissions and it is suggested for further study to determine the scope for its wider applicability.

3 Country studies

For the ten candidate countries selected for study the profile of the current coal fleet has been determined, regional influences on future energy demand researched and a prediction made on the possible level of coal demand over the period to approximately 2040. The results of this analysis are presented below, in alphabetical order.

3.1 Australia

3.1.1 Profile of existing coal fleet

The profile of the Australian coal fleet, abstracted from the WEPP is shown below in Table 4 and Figure 9. Plant units are grouped by age and by steam cycle conditions (subcritical, supercritical and ultra-supercritical). The Australian coal fleet accounts for approximately 2% of the global coal-fired capacity and is responsible for approximately 2% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010).

Table 4 Australian coal-fired power plant by age and steam cycle conditions (MWe)

Period	All steam cycle conditions	Subcritical	Supercritical	Ultra-supercritical
Pre–1940	0	0	0	0
1940–49	30	30	0	0
1950–59	117	117	0	0
1960–69	2610	2610	0	0
1970–79	7133	7133	0	0
1980–89	12973	12973	0	0
1990–94	1913	1913	0	0
1995–99	2263	2263	0	0
2000–04	2393	150	2243	0
2005–09	1216	466	750	0
2010–13	114	114	0	0
Subtotal less planned	**30762**	**27769**	**2993**	**0**
Planned or under construction post-2013	4531	581	0	0
Total	**35292**	**28349**	**2993**	**0**

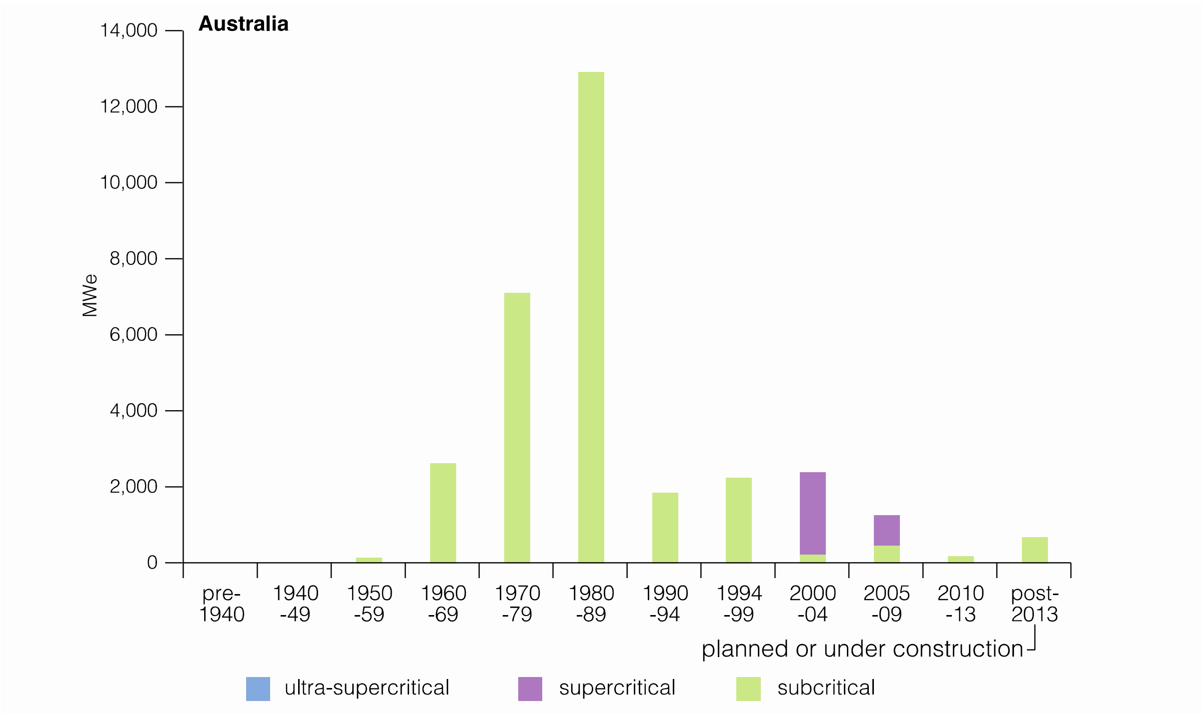

Figure 9 Australian coal-fired power plant by age and steam cycle conditions

The coal fleet has a median age of approximately thirty years and is predominately comprised of subcritical units with some supercritical plant coming online in the last ten years. Among the ten countries examined in this study, Australia is one of the four countries with the lowest share of super- or ultra-supercritical power generation in the installed fleet and currently in operation.

The coal fleet varies considerably in age with some plant having been in service for over 50-years without any plans for retirement. The most efficient plants are in Queensland where four supercritical power plants (Callide C, Milmerran, Tarong North and Kogan Creek) date from 2001. Some of these plants are located in the more arid areas of the state where they are required to have air cooled condensers which have a detrimental effect on thermal efficiency.

Currently, around 70% of electricity generation is by pulverised coal plant with baseload units in New South Wales and Queensland fed by indigenous bituminous coals. Together with plants in Victoria and South Australia, these generators supply the eastern National Electricity market (NEM). The coal plants in Victoria are largely clustered in the southern Latrobe Valley where there is an abundance of lignitic coals. South Australia has two coal-fired generators being supplied with subbituminous fuels from mines in the centre of that state.

It is interesting to note that since the Queensland plants were built, it is reported that there has been a general trend away from high efficiency PCC plants to service potential future energy needs (Morson, 2013). This thought to be due to a number of factors including:

- the adverse political and community reactions to coal based electricity generation;
- the gradual privatisation of generation assets and the reluctance of new owners to invest in new capacity (coupled with the general lack of investment signals);
- the depressed returns to baseload generators from electricity markets, and more recently the decline in baseload demand.

In Australian projections for growth in coal-based generation as little as six years ago a submission to an enquiry dated June 2007 from one of the country's largest (state-owned) generators pointed to the immediate need to develop new coal fired baseload plants (Macquarie Generation, 2007). The submission outlines the need for high efficiency plant with future potential for CCS, but the project is reported as being subject to indefinite postponement.

3.1.2 Regional influences on future energy demand

The Australian government issued a comprehensive 'White Paper' in November 2011, seven years after the release in 2004 of the previous Energy White Paper (Australian Government Department of Industry, 2011). The draft energy policy outlined in the paper provided a review of Australia's future energy needs to 2030 and set out a policy framework to guide the further development of the sector. The government has very recently published a further consultation document, 'Energy White Paper – Issues Paper' (Australian Government Department of Industry, 2013) seeking responses in advance of a full white paper to be published early in 2014. The aim of the consultation is to seek views on how high intensity low emissions electricity generation can be progressed.

Australia is among the most advanced OECD countries with respect to having developed CCS legal and regulatory frameworks. CCS legislation is currently in place at federal level (for injection and storage in Commonwealth waters) and also for CCS activities onshore in a number of states. The Australian Treasury forecasts that fossil fuel-fired plants with carbon capture and storage could provide between 26% and 32% of total electricity generation as part of a low-carbon portfolio in 2050 (IEA, 2012).

3.1.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 5, 6 and 7 and Figures 10, 11 and 12 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 5 Summary of Australian base case scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	166	160	157	152	146	142
CO_2 emissions (Mt)	169	162	159	154	149	144
Coal fleet profile (MWe)						
Subcritical	27769	27769	27769	27769	27769	27769
Supercritical	2993	2993	2993	2993	2993	2993
Ultra-supercritical	0	0	0	0	0	0
AUSC	0	0	0	0	0	0

Figure 10 Australian base case scenario 2015-40

Table 6 Summary of Australian 50-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	166	160	157	152	146	142
CO_2 emissions (Mt)	169	159	154	142	135	117
Coal fleet profile (MWe)						
Subcritical	27769	25012	25012	17879	17879	4906
Supercritical	2993	2993	2993	2993	2993	2993
Ultra-supercritical	0	1900	1900	5900	5900	12500
AUSC	0	0	0	0	0	0

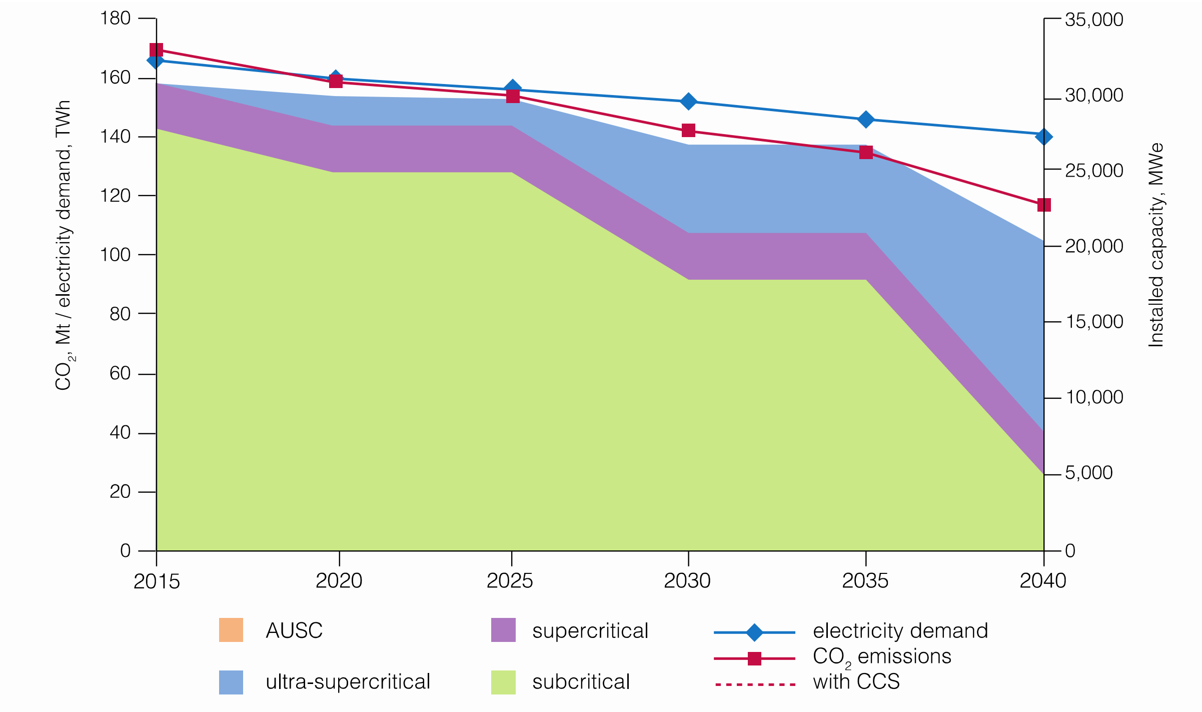

Figure 11 Australian 50-year retirement scenario 2015-40

Table 7 Summary of Australian 25-year retirement scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	166	160	157	152	146	142
CO_2 emissions (Mt)	169	129	127	116	112	108
Coal fleet profile (MWe)						
Subcritical	27769	2993	2993	580	580	0
Supercritical	2993	2993	2993	570	570	0
Ultra-supercritical	0	15600	15600	15600	15600	15600
AUSC	0	0	0	2700	2700	2700

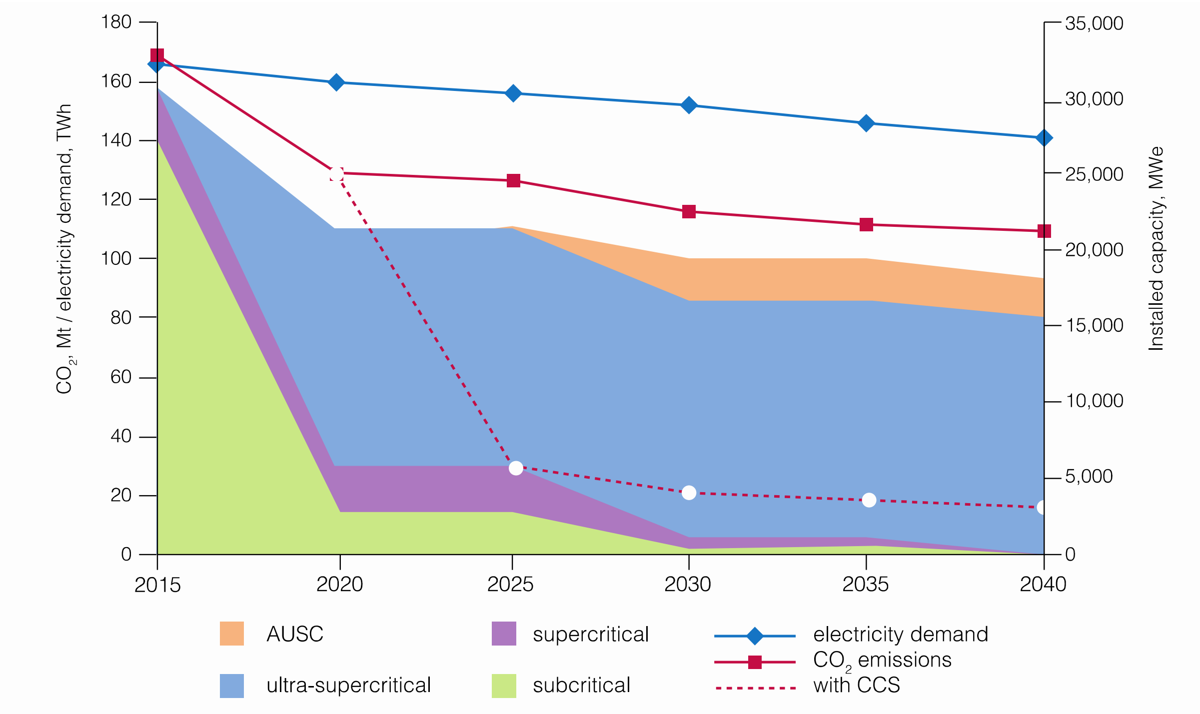

Figure 12 Australian 25-year retirement scenario 2015-40

The Australian scenario is characterised by declining coal-based energy demand common to many OECD countries, and under the base case scenario demand is met using existing capacity without the requirement for new build. Under this scenario, carbon dioxide emissions fall from 169 Mt to 144 Mt (a 15% reduction), in line with the projected fall in demand. Under the 50-year scenario, the introduction of ultra-supercritical units to replace retired plant brings about a progressive decline in emissions of carbon dioxide from 169 Mt in 2015 to 117 Mt in 2040 (a 31% reduction). The 25-year scenario continues this trend with the impact of AUSC units showing, particularly after 2030. Emissions of carbon dioxide under the 25-year scenario fall from 169 Mt to 108 Mt (a 36% reduction). The Australian case, along with the other country examinations also demonstrates a feature of a HELE coal fleet not normally emphasised; a significant reduction in fleet size. Where new HELE units are replacing existing but retired plant, the smaller fleet size may be advantageous in the context of obtaining planning consents where this is traditionally an area of difficulty such as in the OECD countries.

3.2 China

3.2.1 Profile of existing coal fleet

The profile of the Chinese coal fleet, abstracted from the WEPP is shown below in Table 8 and Figure 13. Plant units are grouped by age and by steam cycle conditions (subcritical, supercritical and ultra-supercritical). The Chinese coal fleet dominates global capacity and greenhouse gas emissions and accounts for approximately 41% of the global coal-fired capacity and is responsible for approximately 37% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010). China's coal fleet is by far the youngest fleet currently in operation with a median age of less than twenty years. In addition, a significant fraction of the newer plant employs supercritical or ultra-supercritical steam conditions.

Table 8 Chinese coal-fired power plant by age and steam cycle conditions (MWe)

Period	All steam cycle conditions	Subcritical	Supercritical	Ultra-supercritical
Pre–1940	35	35	35	35
1940–49	24	24	24	24
1950–59	3021	3021	0	0
1960–69	3453	3453	0	0
1970–79	17915	17915	0	0
1980–89	46147	46147	0	0
1990–94	51595	49255	2340	0
1995–99	71794	69054	2740	0
2000–04	97280	89310	7760	0
2005–09	328998	191662	103630	32290
2010–13	179696	61509	57020	60304
Subtotal less planned	**799957**	**531384**	**173549**	**92653**
Planned or under construction post-2013	567344	75252	55790	138522
Total	**1367301**	**606636**	**229339**	**231175**

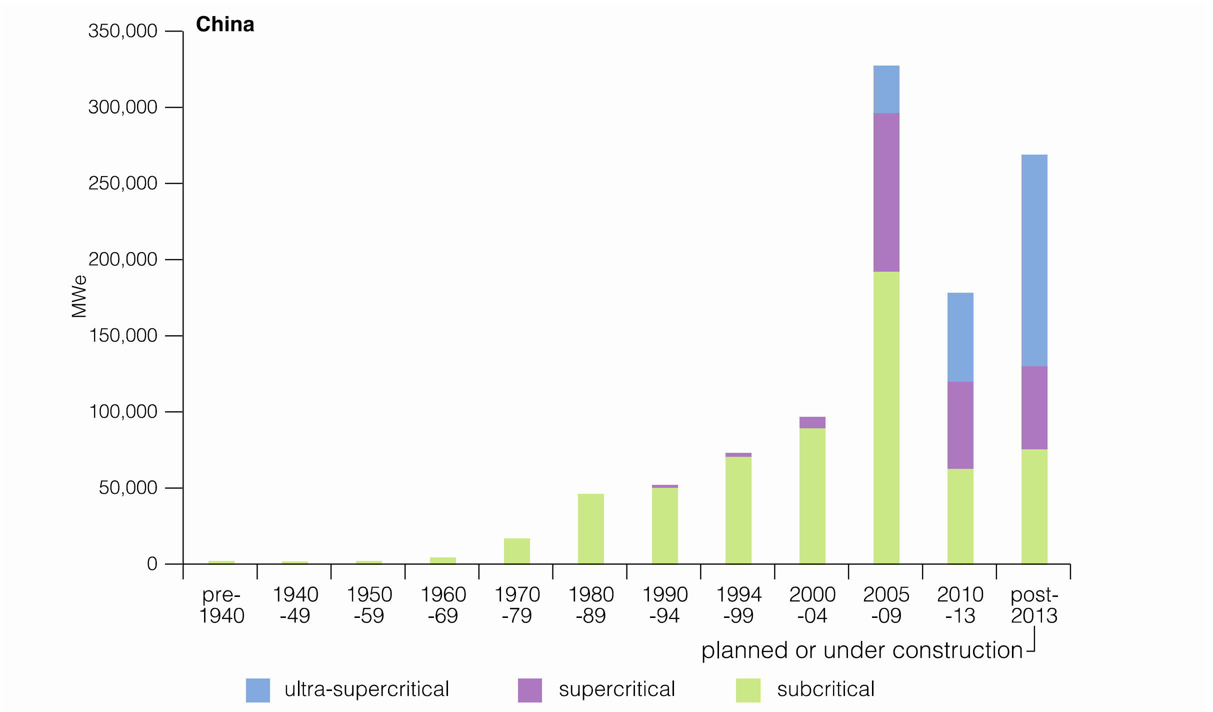

Figure 13 Chinese coal-fired power plant by age and steam cycle conditions

3.2.2 Regional influences on future energy demand

With a reported coal-fired power generation capacity of over 800 GWe, and an annual total of 3723 TWh (2011 data, IEA (2013)), China is the largest producer of electricity from coal in the world. Predictions on the role of coal in China's future energy needs agree that coal will continue to be a very significant contributor to the country's energy needs although there are differences in the relative importance of coal with respect to other primary energy sources. China is actively seeking to diversify its energy supplies although at present, hydroelectric sources (6% of total), natural gas (4%), nuclear power (1%), and other renewables (0.3%) account for relatively small shares of China's energy generation profile. The Chinese government has set a target to raise non-fossil fuel energy consumption to 11.4% of the total energy mix by 2015 as part of its new 12th Five-Year Plan. EIA (2013) projects coal's share of the total energy mix to fall to 59% by 2035 due to anticipated higher energy efficiencies and China's goal to reduce its carbon intensity. However, absolute coal consumption is expected to double over this period, reflecting the large growth in total energy consumption.

The US Energy Information Administration (EIA) (2013) predictions for the growth in coal use for electricity generation foresee an increase from 73 PJ in 2010 (the reference year) to over 128 PJ for an annual growth rate (2010–40) of 1.9%. The highest growth scenario of 3.4% annually predicts that almost 200 PJ of coal could be used in the power sector in 2040.

Zou and others (2011) recently published the results of an extensive study of China's energy situation (all sectors). The study was based on the Lawrence Berkeley National Laboratory's China End-Use Energy Model which deals with various end-use technologies and physical drivers of energy demand. A baseline 'Continued Improvement Scenario' and an alternative energy efficiency scenario 'Accelerated Improvement Scenario' have been developed to assess the impact of actions already taken by the Chinese government as well as planned and potential actions, and to evaluate the potential for China to control energy demand growth and mitigate emissions. In addition, this analysis also evaluated China's long-term domestic energy supply in order to gauge the potential challenge China may face in meeting long-term demand for energy. The principal findings from the study were that with the decline in availability of the easily accessible coal reserves, energy investment per unit of coal extracted will increase. Competition is thought likely to reduce coal's market share and lead to reductions in carbon dioxide emissions in the power sector, primarily from the increase in nuclear, hydropower and renewable generation. Also, end-use efficiency improvements were thought likely to lower final electricity demand and the related carbon dioxide emissions.

3.2.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 9, 10 and 11 and Figures 14, 15 and 16 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 9 Summary of Chinese base case scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	4190	4887	5741	6463	7021	7263
CO_2 emissions (Mt)	3648	4256	4974	5524	6013	6136
Coal fleet profile (MWe)						
Subcritical	531384	531384	531384	531384	531384	531384
Supercritical	173549	173549	173549	173549	173549	173549
Ultra-supercritical	92653	92653	210000	300000	380000	400000
AUSC	0	0	0	0	0	0

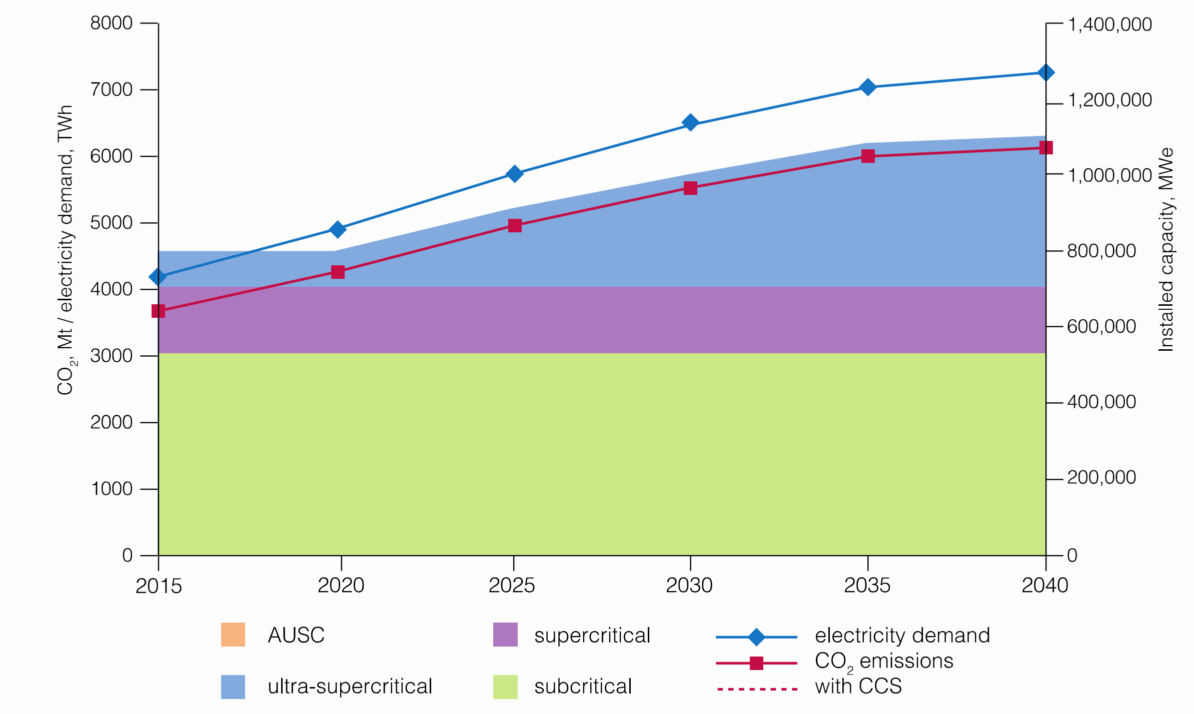

Figure 14 Chinese base case scenario 2015-40

Table 10 Summary of Chinese 50-year retirement scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	4190	4887	5741	6463	7021	7263
CO_2 emissions (Mt)	3648	4188	4860	5404	5832	6025
Coal fleet profile (MWe)						
Subcritical	531384	524851	524851	506936	506936	460789
Supercritical	173549	173490	173490	173490	173490	173490
Ultra-supercritical	92653	185000	295000	395000	465000	525000
AUSC	0	0	0	0	0	0

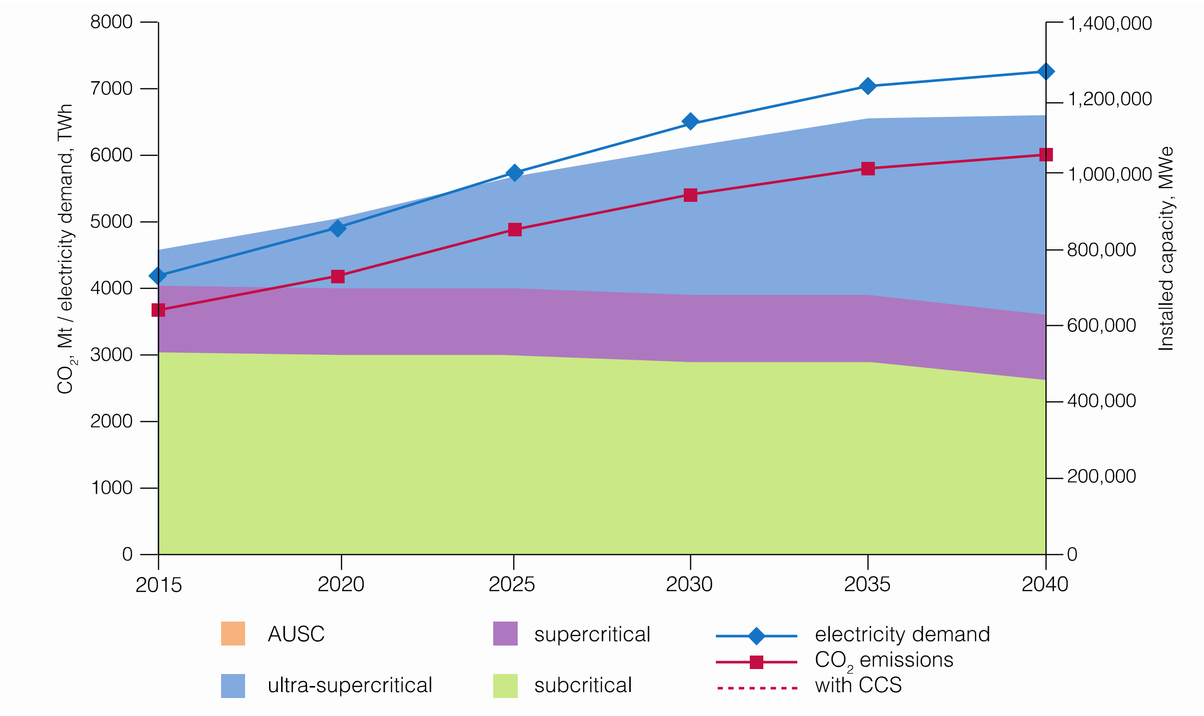

Figure 15 Chinese 50-year retirement scenario 2015-40

Table 11 Summary of Chinese 25-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	4190	4887	5741	6463	7021	7263
CO_2 emissions (Mt)	3648	4114	4695	5012	5376	5002
Coal fleet profile (MWe)						
Subcritical	531384	411535	411535	253171	253171	0
Supercritical	173549	171150	171150	160650	160650	0
Ultra-supercritical	92653	245000	245000	245000	245000	152347
AUSC	0	0	110000	295000	364000	770000

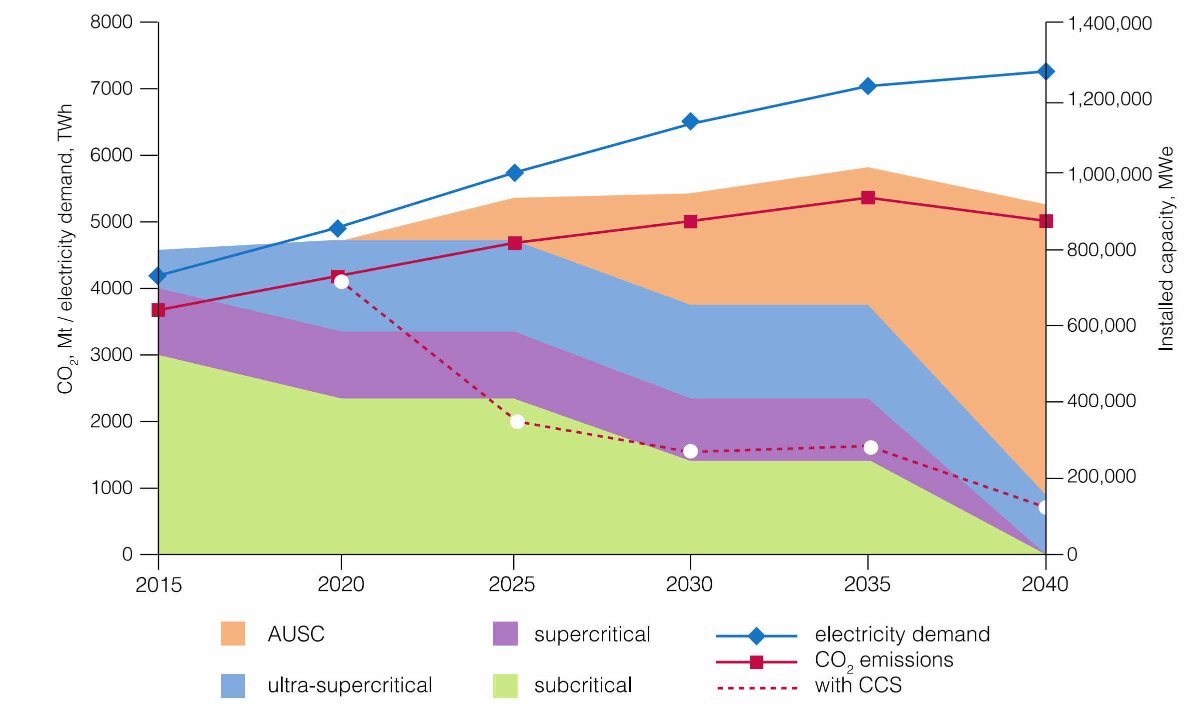

Figure 16 Chinese 25-year retirement scenario 2015-40

The Chinese scenario is characterised by continuing rapid growth in coal-based energy demand almost doubling by 2040, although the projected increase begins to level off after 2035. Under the base case scenario, demand cannot be met using existing capacity and new ultra-supercritical plant is required to meet predicted shortfall. Emissions of carbon dioxide under this scenario increase from 3648 Mt in 2015 to 6136 Mt in 2040 (a 68% increase). The relative youth of the Chinese coal fleet is demonstrated in the 50-year scenario, where the impact of plant retirements has a muted impact on emissions, unsurprising as the Chinese fleet is rapidly transitioning to a HELE profile. Emissions of carbon dioxide under this scenario increase from 3648 Mt in 2015 to 6025 Mt in 2040 (a 65% increase). Although the current and near future Chinese coal fleet contains a significant proportion of state-of-the-art plant, the 25-year scenario emphasises the impact of further efficiency improvements as a large tranche of AUSC plant replaces older units from 2025 onwards. Under this scenario, emissions of carbon dioxide range from 3648 Mt in 2015 to 5002 Mt in 2040 (a 37% increase), despite an increasing trend in demand.

3.3 Germany

3.3.1 Profile of existing coal fleet

The profile of the German coal fleet, abstracted from the WEPP is shown below in Table 12 and Figure 17. Plant units are grouped by age and by steam cycle conditions (subcritical, supercritical and ultra-supercritical). The German coal fleet accounts for approximately 3% of the global coal-fired capacity and is responsible for approximately 3% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010). The German coal fleet is the fourth largest coal-fired power plant fleet installed in a single country. The median plant life is approximately twenty five years and four out of five of the coal-fired power plants currently in operation are older than 20 years. Supercritical units have featured in the coal fleet since the 1960s and the most recently installed units are predominately based on this technology. In addition to 2.7 GW of lignite capacity that became operational in 2012, a further 8GW of new coal capacity is currently under construction and expected to commission by 2015. However, this new build is not a recent development, and has arisen largely from unusual historical reasons:

- a favourable market environment in 2007/8;
- a temporary presumption of free carbon allowances for new build plants in Phase III of the EU ETS and ;
- a reported inability (Heinrich and Hare (2013)) or reluctance of the plant developers to cancel projects when the circumstances changed and when technical problems delayed their build.

Escalating capital costs, local and environmental opposition, the high priority being given to renewables, the economic downturn, falling electricity demand, low wholesale electricity prices and the expectation of high carbon prices in the future make the short- and long-term investment cases for new thermal plants in Germany unattractive. While there are reportedly 2.7 GW of coal or lignite projects under development, most of projects have stalled, suggesting likely cancellation. Since 2007, four coal and lignite projects have been postponed and a further twenty two abandoned as a result of the unfavourable circumstances described above.

Table 12 German coal-fired power plant by age and steam cycle conditions (MWe)

Period	All steam cycle conditions	Subcritical	Supercritical	Ultra-supercritical
Pre–1940	0	0	0	0
1940–49	0	0	0	0
1950–59	1086	1086	0	0
1960–69	7293	6943	350	0
1970–79	14706	13327	1379	0
1980–89	16168	14719	1449	0
1990–94	2458	1948	510	0
1995–99	4676	283	4394	0
2000–04	2963	111	1840	1012
2005–09	87	87	0	0
2010–13	9072	44	911	8117
Subtotal less planned	**58509**	**38547**	**10833**	**9129**
Planned or under construction post-2013	11764	722	4820	5562
Total	**70273**	**39269**	**15653**	**14691**

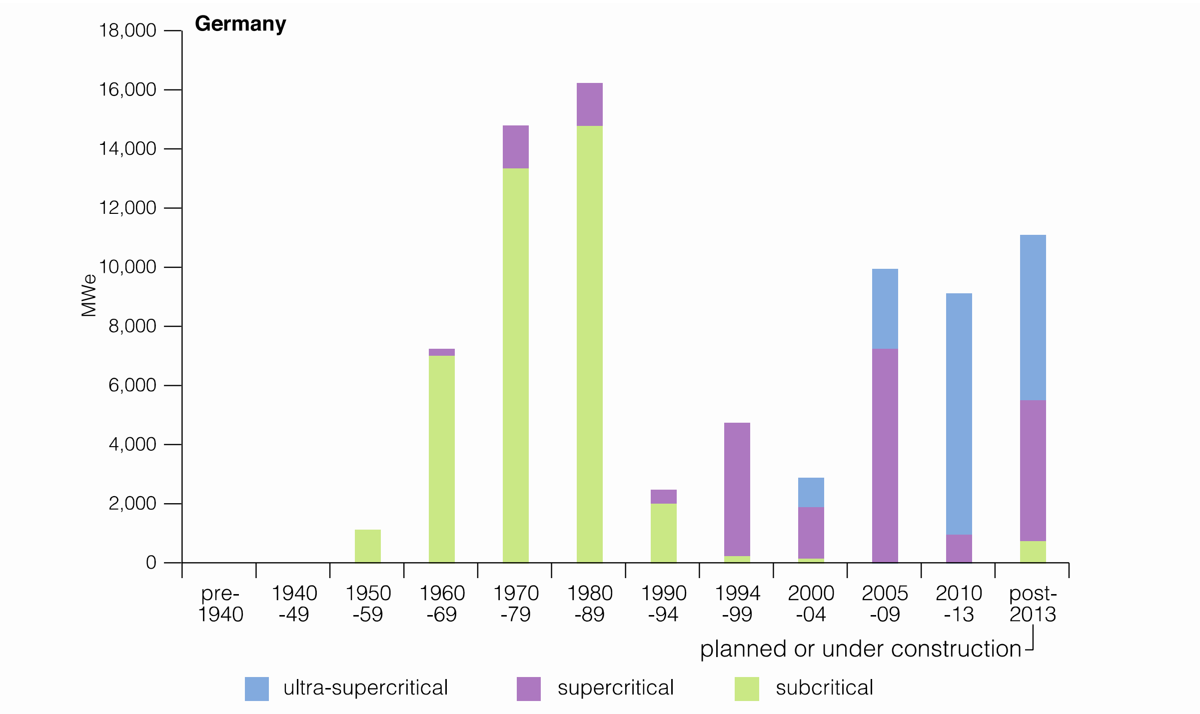

Figure 17 German coal-fired power plant by age and steam cycle conditions

3.3.2 Regional influences on future energy demand

Heinrich and Hare (2013) recently studied the prospects for new coal-fired power stations in Germany, the Netherlands and Spain. Reviewing the German energy policy 'Energiewende', published in 2011, the German Government changed the direction of its energy policy and announced aims to move away from nuclear and fossil fuels towards a system dominated by renewables generation and efficient use of energy. Following the Fukushima nuclear accident in March 2011, the German government announced its intention to accelerate the phase-out of Germany's nuclear fleet by 2022 starting with the immediate closure of the eight oldest plants. The cornerstones of the Energiewende are the exit from nuclear power by 2022 and speeding up the implementation of the 'Energy Concept' which sets out sets targets and specific activities to hit them. Energy efficiency is an important pillar of the Energiewende and the country has set a target of 20% reduction in primary energy consumption by 2020 and 50% by 2050 (reference year 2008). A regulatory framework for CCS has been established although progress to date has been slow and some planned projects have been cancelled. The recent development follows falling coal use in North America as a result of the boom in shale gas, where exports of American coal are increasing its use in Europe. Recent evidence suggests that German utilities are consuming larger volumes of coal and displacing natural gas from the generation mix which is likely to increase Germany's GHG emissions while inhibiting investment in relatively lower emission gas-fired technologies.

3.3.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 13, 14 and 15 and Figures 18, 19 and 20 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 13 Summary of German base case scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	189	193	197	200	204	208
CO_2 emissions (Mt)	172	175	178	181	185	188
Coal fleet profile (MWe)						
Subcritical	38547	38547	38547	38547	38547	38547
Supercritical	10833	10833	10833	10833	10833	10833
Ultra-supercritical	9129	9129	9129	9129	9129	9129
AUSC	0	0	0	0	0	0

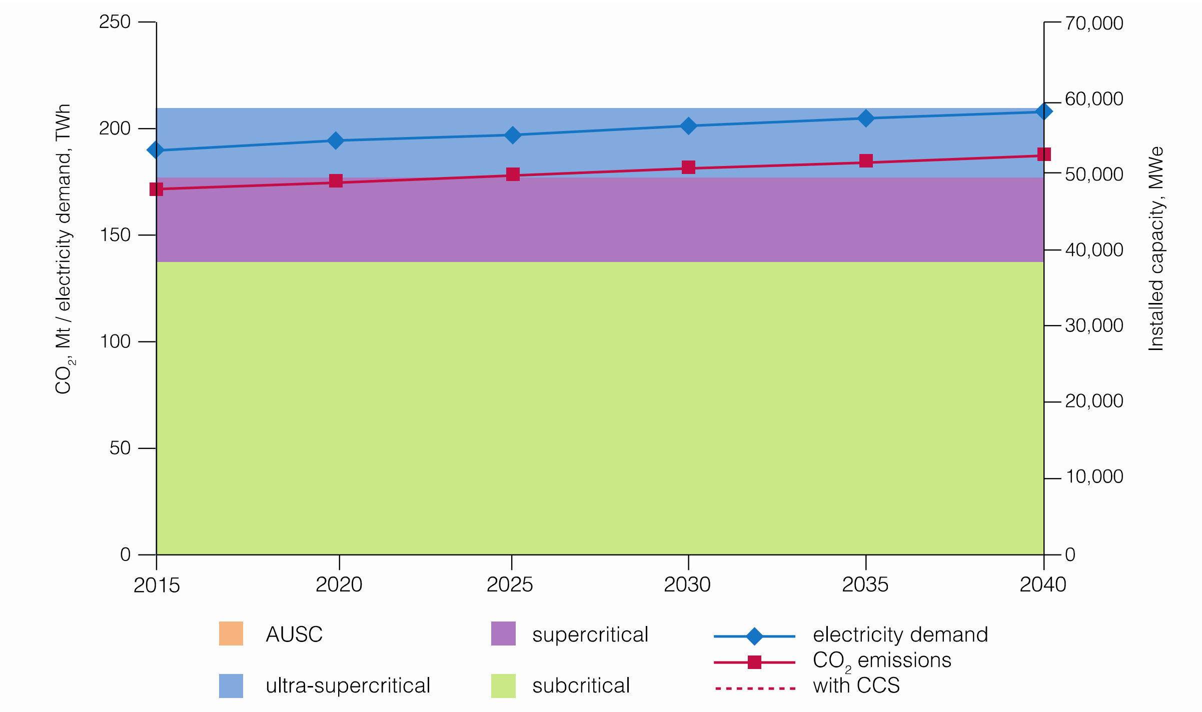

Figure 18 German base case scenario 2015-40

Table 14 Summary of German 50-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	189	193	197	200	204	208
CO_2 emissions (Mt)	172	172	175	179	182	167
Coal fleet profile (MWe)						
Subcritical	38547	30519	30519	17191	17191	2473
Supercritical	10833	10483	10483	9104	9104	7655
Ultra-supercritical	9129	9129	9129	9129	9129	18300
AUSC	0	0	0	0	0	0

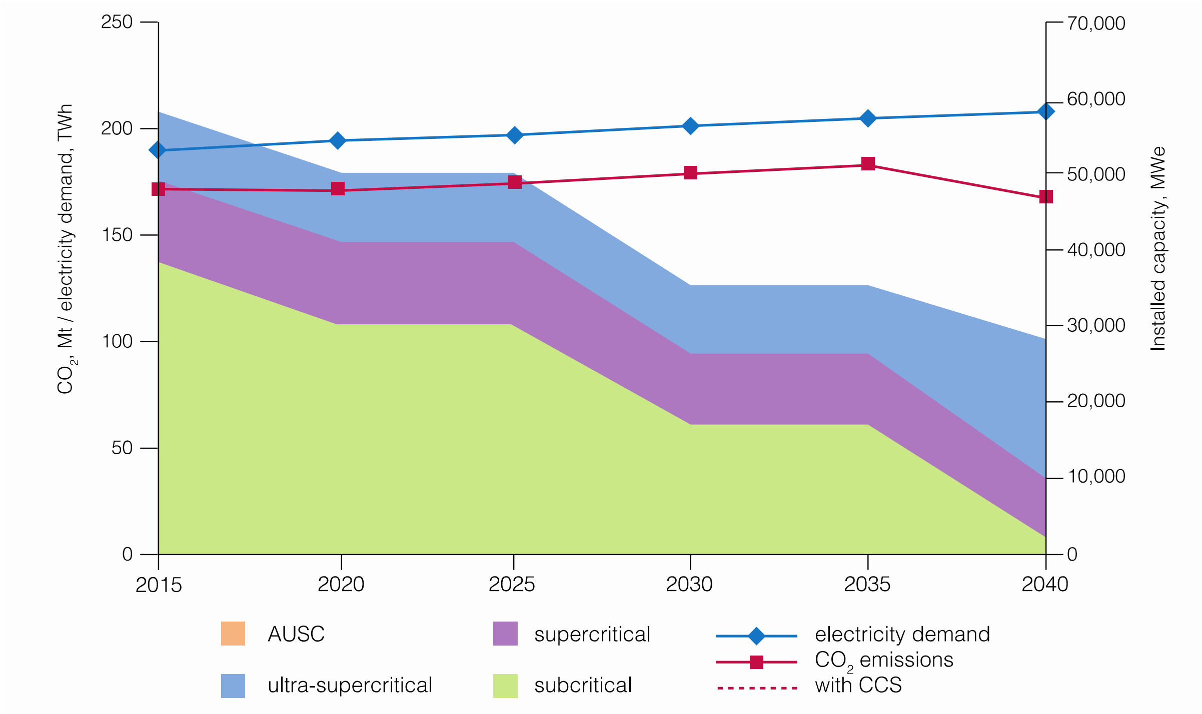

Figure 19 German 50-year retirement scenario 2015-40

Table 15 Summary of German 25-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	189	193	197	200	204	208
CO_2 emissions (Mt)	172	149	152	152	154	149
Coal fleet profile (MWe)						
Subcritical	38547	525	525	131	131	0
Supercritical	10833	7145	7145	911	911	0
Ultra-supercritical	9129	20300	20300	20300	20300	11171
AUSC	0	0	0	4600	5100	15200

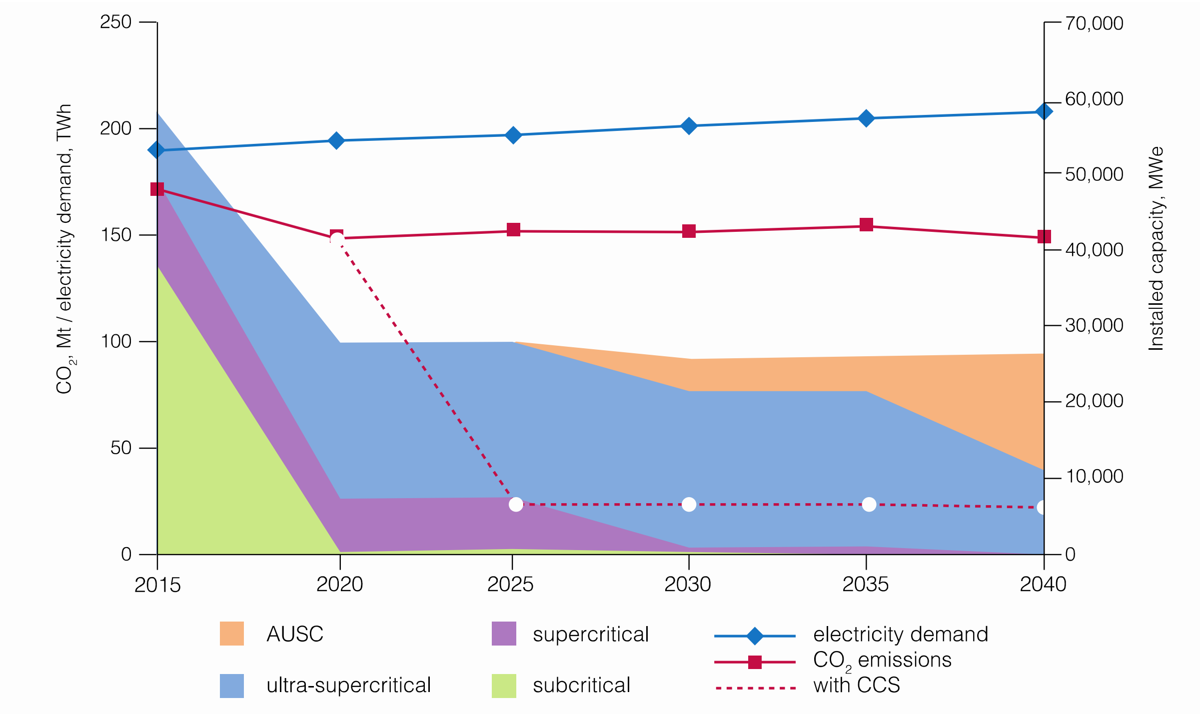

Figure 20 German 25-year retirement scenario 2015-40

With modest growth predicted for the German economy, the local scenario is characterised by an increasing coal-based energy demand. Under the base case scenario, demand is met using existing capacity without the requirement for new build. Carbon dioxide emissions in the base case are characterised by an increase from 172 Mt in 2015 to 188 Mt in 2040 (an increase of 9%). In the 50-year plant retirement case a tranche of subcritical units operating on relatively low load factor is replaced by higher efficiency plant operating at a higher load factor giving rise to a reduced sized coal fleet. Emissions range from 172 Mt to 167 Mt, a decrease of 3% against an increasing trend in demand. Under the 25-year scenario the impact of further HELE capacity reduces emissions from 172 Mt in 2015 to 149 Mt in 2040, a decrease of 13%.

In the interests of a consistent country approach through the study, specific coal types have not been disaggregated from the fleet profile. In the German case, a significant lignite-burning capacity is installed and existing plant could benefit by the efficiency improvements through the utilisation of the lignite drying technologies outlined earlier in addition to any steam cycle improvements. Recent work (RWE, 2010) suggests that efficiency improvements of 4–6% points are achievable. It is issues such as this that merit deeper analysis in the proposed series of individual HELE country studies.

3.4 India

3.4.1 Profile of existing coal fleet

India has the third largest coal fleet installed in a single country. The profile of the Indian coal fleet, abstracted from the WEPP is shown below in Table 16 and Figure 21. Plant units are grouped by age and by steam cycle conditions (subcritical, supercritical and ultra-supercritical). The Indian coal fleet contributes significantly to greenhouse gas emissions and accounts for approximately 6% of the global coal-fired capacity with approximately 8% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010). Indian plants have a comparably high share of generation units with relatively small generation capacity and many of the units burn high ash coal (up to 50%). The majority of the Indian coal-fired power plant fleet is based on subcritical technology but recent builds incorporate supercritical steam cycles. The fleet is relatively young and a very large portfolio of supercritical plants is reported as planned or under construction which will lead to Indian being the second fastest growing user of coal for electricity generation (after China) by 2020 (IEA,2012).

Table 16 Indian coal-fired power plant by age and steam cycle conditions (MWe)

Period	All steam cycle conditions	Subcritical	Supercritical	Ultra-supercritical
Pre–1940	144	144	0	0
1940–49	194	194	0	0
1950–59	648	648	0	0
1960–69	4933	4933	0	0
1970–79	8466	8466	0	0
1980–89	27347	27347	0	0
1990–94	10423	10423	0	0
1995–99	11262	11239	0	0
2000–04	7785	7785	0	0
2005–09	23249	23249	0	0
2010–13	92343	67793	67793	0
Subtotal less planned	**186791**	**162218**	**67793**	**0**
Planned or under construction post-2013	73538	27648	44090	0
Total	**260329**	**189866**	**111883**	**0**

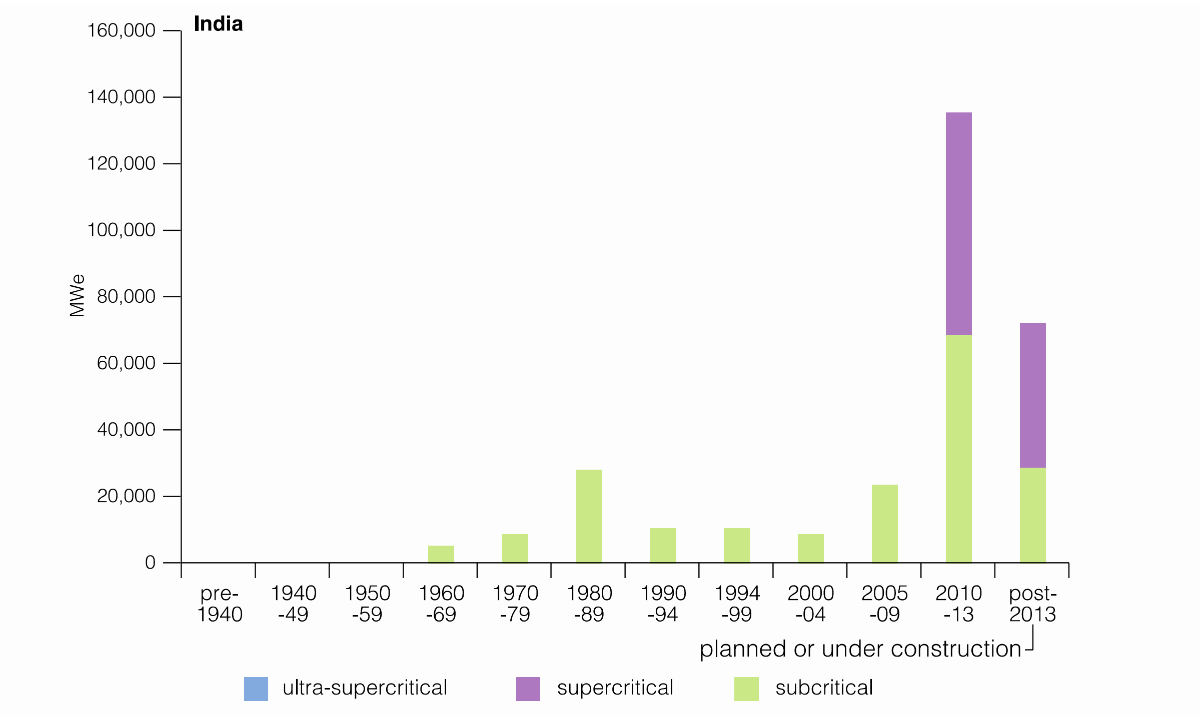

Figure 21 Indian coal-fired power plant by age and steam cycle conditions

3.4.2 Regional influences on future energy demand

India's Integrated Energy Policy (IEP) of 2008 was a comprehensive drive to cover all energy sectors in the Indian economy. The brief for the policy review was 'to prepare an integrated energy policy linked with sustainable development that covers all sources of energy and addresses all aspects of energy use and supply including energy security, access and availability, affordability and pricing, as well as efficiency and environmental concerns' (Indian Planning Commission, 2006). One of the key directions set for the long-term energy strategy is the validation of coal as a primary energy source for the long term and the necessity of ensuring coal supply with consistent quality. Power sector reform was strongly emphasised in relation to cost reduction and the rationalisation of fuel prices. The approach for energy security was based on greater exploration or utilisation of domestic resources, namely oil, gas, coal, thorium and renewables.

India's 12th Five-Year Plan (2012–17) contains a target that 50% to 60% of coal plants must use supercritical technology, although observers suggest that significantly less is likely to be achieved in practice. Early indications of India's longer-term policy direction suggest that the 13th Five-Year Plan (2017–22) will stipulate that *all* new coal-fired plants constructed must be at least supercritical and that no new subcritical plants would be allowed (George, 214). However, it is suggested that the development and deployment of these efficient technologies is sluggish, due to Indian coal which has high ash content and low calorific value.

3.4.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 17, 18 and 19 and Figures 22, 23 and 24 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 17 Summary of Indian base case scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	704	810	957	1112	1306	1524
CO_2 emissions (Mt)	764	858	1004	1124	1276	1444
Coal fleet profile (MWe)						
Subcritical	162218	162218	162218	162218	162218	162218
Supercritical	67793	67793	67793	67793	67793	67793
Ultra-supercritical	0	0	0	19700	44500	72000
AUSC	0	0	0	0	0	0

Figure 22 Indian base case scenario 2015-40

Table 18 Summary of Indian 50-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	704	810	957	1112	1306	1524
CO_2 emissions (Mt)	764	853	985	1065	1215	1348
Coal fleet profile (MWe)						
Subcritical	162218	156300	156300	147834	147834	120487
Supercritical	67793	67793	67793	67793	67793	67793
Ultra-supercritical	0	0	0	57500	82000	119600
AUSC	0	0	0	0	0	0

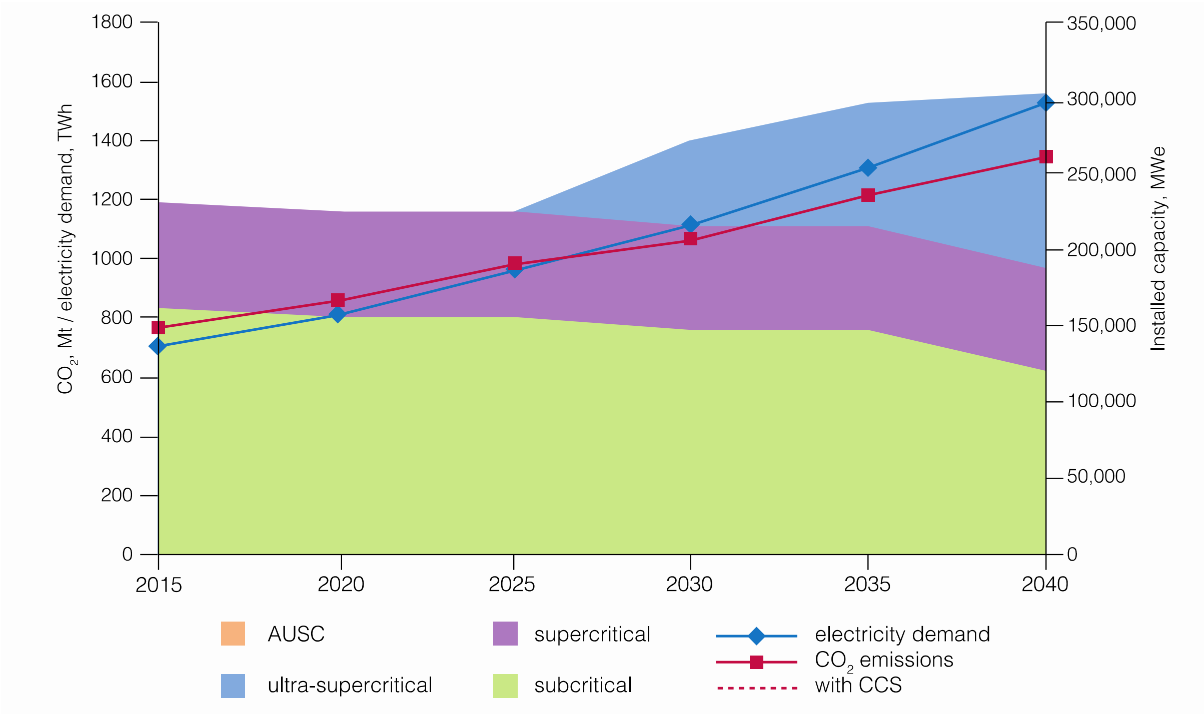

Figure 23 Indian 50-year retirement scenario 2015-40

Table 19 Summary of Indian 25-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	704	810	957	1112	1306	1524
CO_2 emissions (Mt)	764	784	899	973	1103	1063
Coal fleet profile (MWe)						
Subcritical	162218	110065	110065	91041	91041	0
Supercritical	67793	67793	67793	67793	67793	0
Ultra-supercritical	0	33200	52000	52000	52000	52000
AUSC	0	0	0	26700	51300	141000

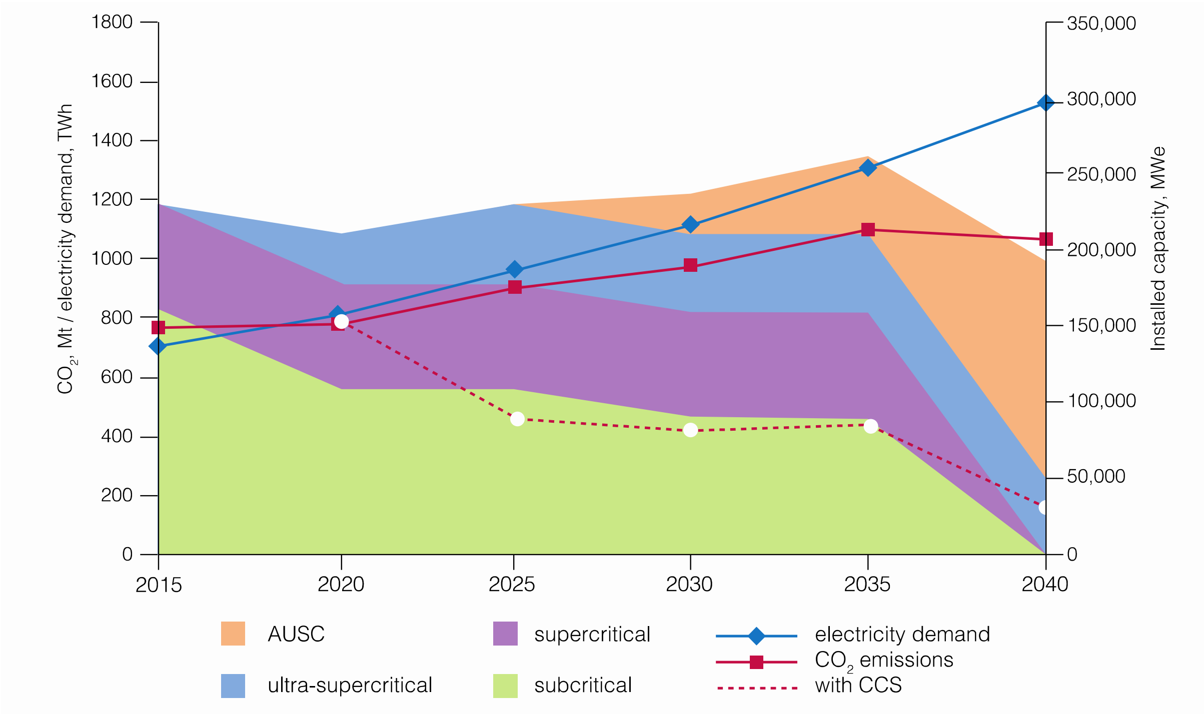

Figure 24 Indian 25-year retirement scenario 2015-40

As a rapidly developing country, India shares many characteristics with China. A rapid growth in coal-based energy demand extends to 2040 and shows no sign of levelling off. Under the base case scenario, demand cannot be met using existing capacity and new ultra-supercritical plant is required. Emissions of Carbon dioxide rise in line with the projected demand from 764 Mt to 1444 Mt under this scenario (an 89% increase). Under the 50-year scenario, new ultra-supercritical units are required but again complement rather than replace the relatively youthful existing stock. Again in a similar pattern to that for China, emissions of carbon dioxide emissions continue to rise under the 50-year scenario but are mitigated by the widespread adoption of the higher efficiency plants ranging from 764 Mt in 2015 to 1349 Mt in 2040 (a 76% increase). Finally, when AUSC is introduced into the plant mix, emissions first level out and then decline, despite the increasing demand trend; 764 Mt in 2015 to 1063 Mt in 2040 (a 39% increase).

3.5 Japan

3.5.1 Profile of existing coal fleet

The profile of the Japanese coal fleet, abstracted from the WEPP is shown below in Table 20 and Figure 25. Plant units are grouped by age and by steam cycle conditions (subcritical, supercritical and ultra-supercritical). The Japanese coal fleet accounts for approximately 2% of the global coal-fired capacity and is responsible for approximately 3% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010). For an OECD country, Japan has a relatively young coal fleet with a high proportion of supercritical and ultra-supercritical units. All plants burn imported coal.

Table 20 Japanese coal-fired power plant by age and steam cycle conditions (MWe)

Period	All steam cycle conditions	Subcritical	Supercritical	Ultra-supercritical
Pre–1940	0	0	0	0
1940–49	0	0	0	0
1950–59	83	83	0	0
1960–69	2015	2015	0	0
1970–79	2625	2625	0	0
1980–89	6561	1961	4600	0
1990–94	6436	636	4500	1300
1995–99	5903	1003	3200	1700
2000–04	13637	1947	4690	7000
2005–09	1762	655	507	600
2010–13	2516	16	1600	900
Subtotal less planned	**41536**	**10939**	**19097**	**11500**
Planned or under construction post-2013	2233	233	400	600
Total	**43769**	**11172**	**19497**	**12100**

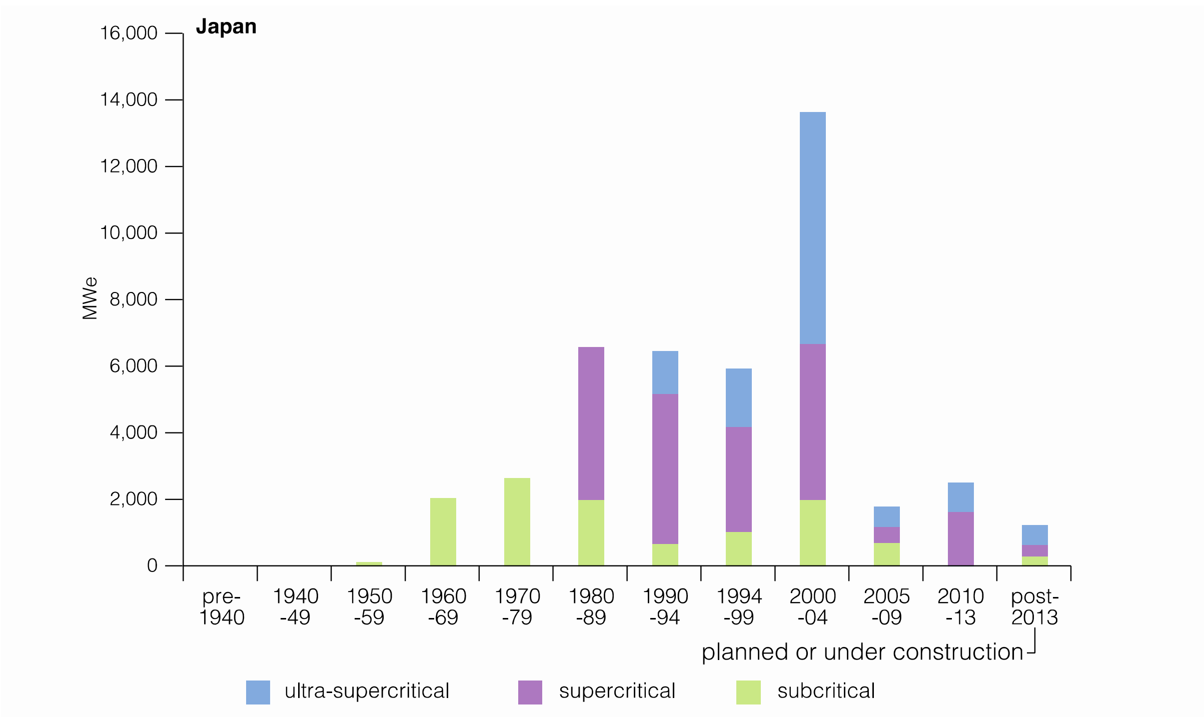

Figure 25 Japanese coal-fired power plant by age and steam cycle conditions

3.5.2 Regional influences on future energy demand

In June 2013 the Japanese Government announced a wide-ranging series of policy initiatives aimed at revitalising the Japanese economy (Nippon.com, 2013). The plan set out the need to review and restructure, if necessary, Japan's primary sources of energy in the light of the accident at the Fukushima nuclear power station. The Advisory Committee of METI for Natural Resources and Energy established the new Basic Energy Plan on 6 December 2013 and this is to be discussed and ratified early in 2014 (Yamamoto, 2013). The plan states that nuclear power generation is still a very important power source to the Japanese economy, but it does not indicate the likely proportion of power to be supplied from nuclear plants. Announcing the Basic Energy Plan, Mr Mogi, Minister of Economy Trade and Industry, outlined the aims of the plan at a Press conference on 25 October 2013.

'We are discussing the features and positions about each energy supply. We will decide the target of the best-mix in three years and implement it in ten years. The target will be decided on the basis of introduction of renewable energy and the condition of reoperation of nuclear Power Generation. If we could know the target sooner, we could accelerate its implementation.'

With respect to future coal use, the plan notes the issues associated with greenhouse gas emissions from coal, but also that it has the great advantage in that the supply of coal is likely to remain stable, and its unit energy cost is lower than other fuels. Therefore, coal is being re-evaluated as one of the important base energy sources, but with appropriate coal utilisation technology to minimise the environmental impact of coal use.

Furthermore, the plan notes that a programme of the replacement of the older power plants with new higher efficiency plants will be brought forward, as well as the construction of new power plants to meet future energy needs. Technical research will continue to increase the efficiency of power generation to progressively reduce greenhouse gas emissions.

Environmental impact assessments required for the construction of new power plant current take approximately three years in Japan. The initiatives in the Basic Energy Plan aim to shorten this to just over one year.

Describing government initiatives for the continuing implementation of high efficiency plant, Mr Takayuki Sumita (Director-General, Natural Resources and Fuel Department, ANRE, METI) stated that:

- The government aims to achieve the practical use of advanced ultra-supercritical (AUSC) thermal power generation in the 2020s (generating efficiency: around 39% at present to improve to around 46%).
- The government aims to achieve the practical use of integrated coal gasification combined cycle (IGCC) power generation systems of 1500°C class in the 2020s (generating efficiency: around 39% at present to improve to around 46%).
- The government aims to establish the technology of integrated coal gasification fuel cell combined cycle (IGFC) by 2025 and achieve practical use in the 2030s (generating efficiency: around 39% at present to improve to around 55%).
- For LNG thermal power generation, the government aims to achieve the practical use of gas turbines of the 1700°C class by around 2020 (generating efficiency: around 52% at present to improve to around 57%). (Sumita, 2013)

3.5.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 21, 22 and 23 and Figures 26, 27 and 28 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 21 Summary of Japanese base case scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	305	285	276	266	257	248
CO_2 emissions (Mt)	258	239	231	221	214	207
Coal fleet profile (MWe)						
Subcritical	10939	10939	10939	10939	10939	10939
Supercritical	19097	19097	19097	19097	19097	19097
Ultra-supercritical	11500	11500	11500	11500	11500	11500
AUSC	0	0	0	0	0	0

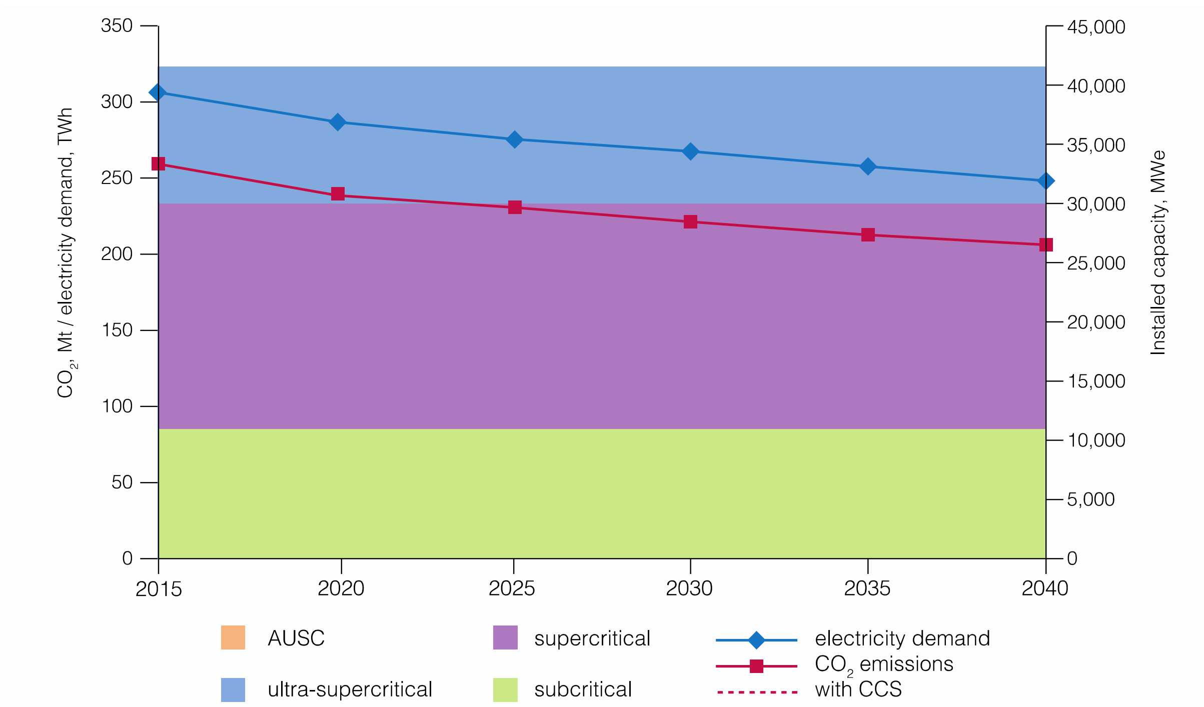

Figure 26 Japanese base case scenario 2015-40

Table 22 Summary of Japanese 50-year retirement scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	305	285	276	266	257	248
CO_2 emissions (Mt)	258	239	230	221	212	202
Coal fleet profile (MWe)						
Subcritical	10939	8842	8842	6217	6217	4256
Supercritical	19097	19097	19097	19097	19097	14497
Ultra-supercritical	11500	11500	11500	11500	11500	15600
AUSC	0	0	0	0	0	0

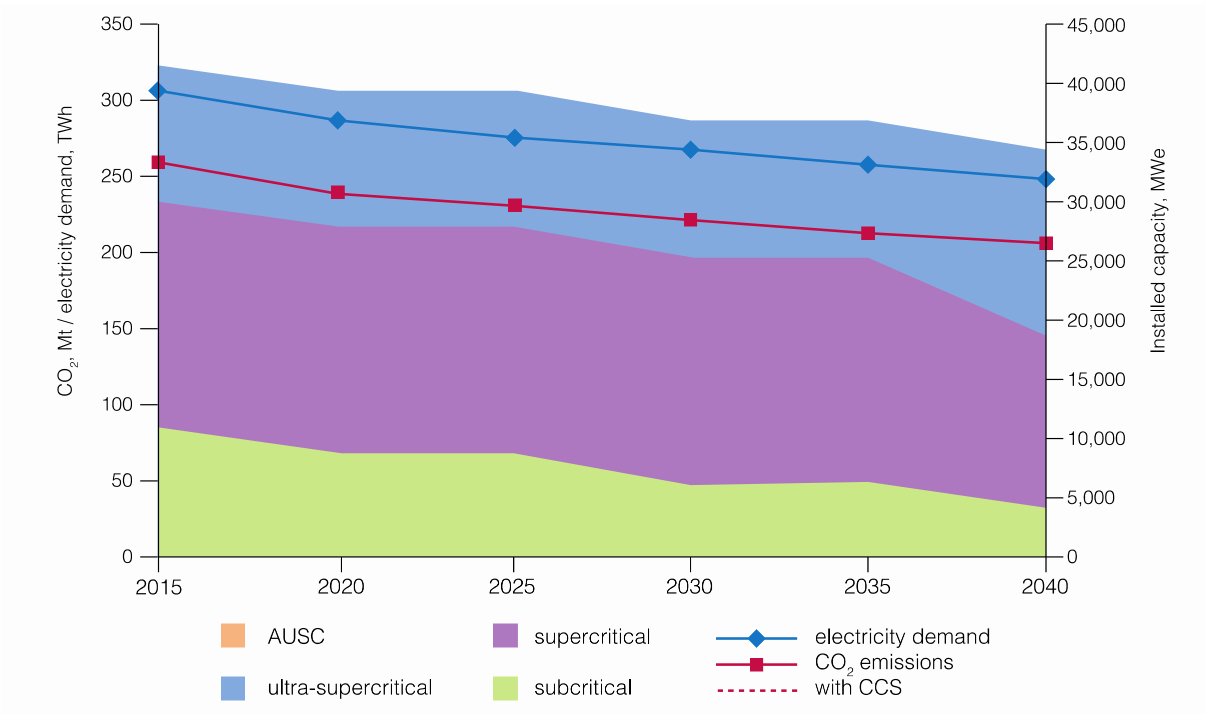

Figure 27 Japanese 50-year retirement scenario 2015-40

Table 23 Summary of Japanese 25-year retirement scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	305	285	276	266	257	248
CO_2 emissions (Mt)	258	230	221	201	194	185
Coal fleet profile (MWe)						
Subcritical	10939	3620	3620	620	620	0
Supercritical	19097	9997	9997	2107	2107	0
Ultra-supercritical	11500	23700	23700	23350	23350	22550
AUSC	0	0	0	8100	8100	8900

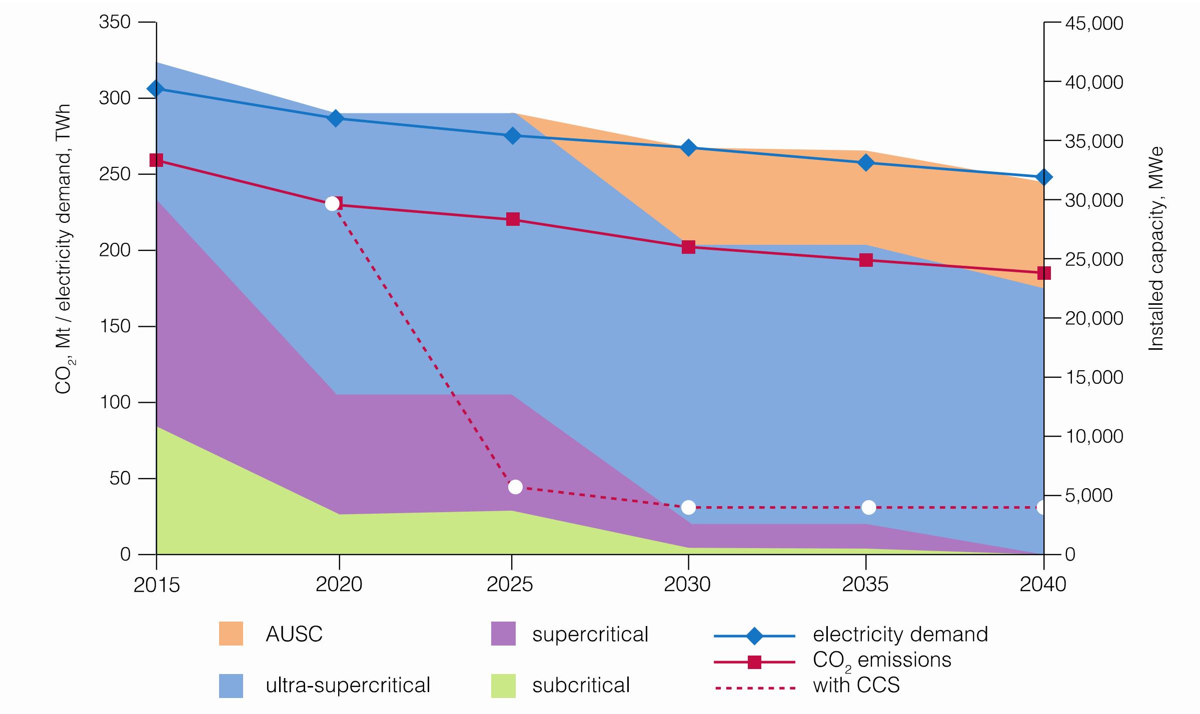

Figure 28 Japanese 25-year retirement scenario 2015-40

The Japanese coal-fired electricity sector is characterised by a falling demand being met by a youthful and efficient coal fleet. Emissions of carbon dioxide decline in line with demand in the base case from 258 Mt in 2015 to 207 Mt in 2040 (a 20% reduction). Some slight reduction in carbon dioxide emissions is seen in the 50-year scenario as older plant is retired and replaced. Emissions under this scenario fall from 258 Mt in 2015 to 202 Mt in 2040 (a 22% reduction). Under the 25-year scenario, AUSC plant begins to replace older capacity from 2030 onwards and emissions fall correspondingly from 258 Mt to 185 Mt (a 28% reduction).

3.6 Poland

3.6.1 Profile of existing coal fleet

Poland is heavily dependent on coal for primary energy production. The profile of the Polish coal fleet, abstracted from the WEPP is shown below in Table 24 and Figure 29. Plant units are grouped by age and by steam cycle conditions (subcritical, supercritical and ultra-supercritical). The coal fleet is dominated by subcritical plants that are relatively old. The Polish coal fleet accounts for approximately 2% of the global coal-fired capacity and is responsible for approximately 2% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010). In recent years, a number of supercritical plants have been commissioned and a large number are reported as being in the planning stage, or under construction. Additionally, many of the older units are relatively small, although these are being progressively replaced.

Table 24 Polish coal-fired power plant by age and steam cycle conditions (MWe)				
Period	**All steam cycle conditions**	**Subcritical**	**Supercritical**	**Ultra-supercritical**
Pre–1940	132	132	0	0
1940–49	147	147	0	0
1950–59	1468	1468	0	0
1960–69	5215	5215	0	0
1970–79	12415	12415	0	0
1980–89	7167	7167	0	0
1990–94	1403	1403	0	0
1995–99	1773	1773	0	0
2000–04	873	873	0	0
2005–09	759	290	469	0
2010–13	1489	171	1318	0
Subtotal less planned	**32839**	**31052**	**1787**	**0**
Planned or under construction post-2013	15071	843	10888	0
Total	**47910**	**31895**	**12675**	**0**

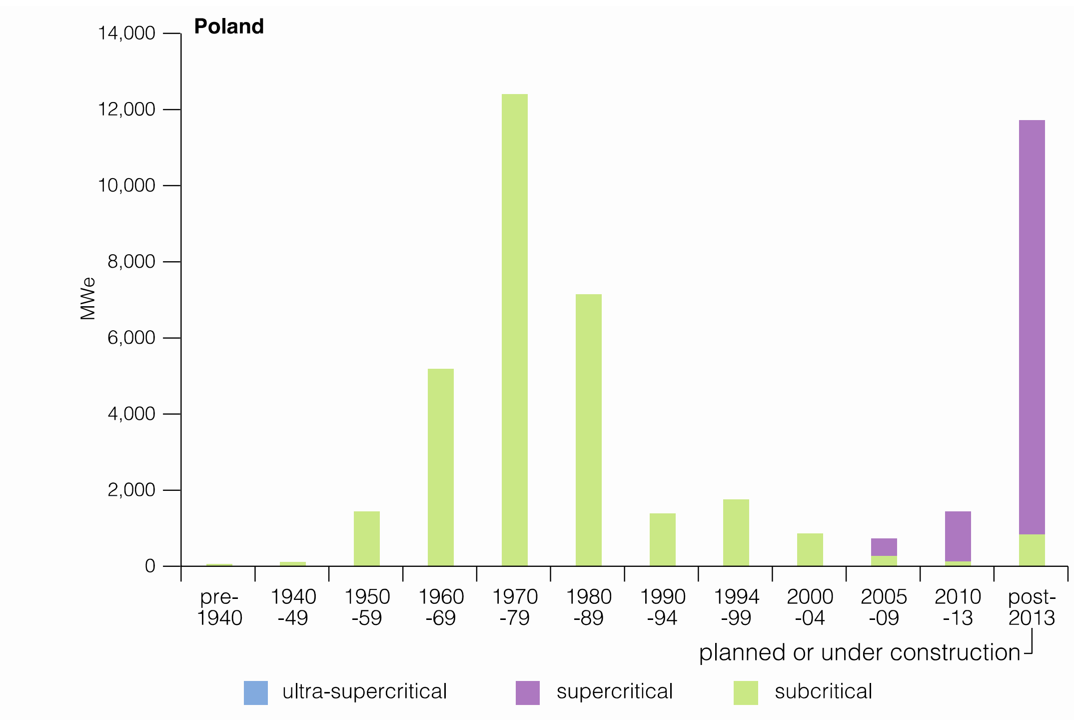

Figure 29 Polish coal-fired power plant by age and steam cycle conditions

The Polish government have published a comprehensive guidance document, Energy Policy of Poland until 2030, which outlines the future direction of Polish energy policy to achieve energy security, environmental sustainability and economic development (Polish Ministry of Economy, 2009). Poland has based its primary energy on domestic resources and the country relies heavily on indigenous coal that accounts for 55% of its primary energy supply and 90% of electricity generation. Poland therefore faces serious issues associated with its high coal use because of high emissions of carbon dioxide at a time when other EU Member States are making significant progress in reducing reliance on fossil energy. Hard coal production is likely to decrease considerably by 2030 and lignite production will also fall sharply by 2030 and shortages can be expected from 2015 onwards, unless new mines are opened. In 2008, Poland became a net hard coal importer for the first time as coal production was insufficient to meet demand. Imports from Russia have surged and accounted for 70% of total coal imports in 2009.

Recent surveys suggest that Poland may have large resources of shale gas. If these resources are confirmed, they could give Poland an opportunity to reduce its import dependence and to change its fuel mix away from coal in the medium and long term. If reserves are significant a situation comparable to that which has developed in the US in the last few years with gas replacing coal and Poland becoming a net exporter of coal.

3.6.2 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 25, 26 and 27 and Figures 30, 31 and 32 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 25 Summary of Polish base case scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	143	146	148	151	154	157
CO_2 emissions (Mt)	156	159	162	166	169	172
Coal fleet profile (MWe)						
Subcritical	31052	31052	31052	31052	31052	31052
Supercritical	1787	1787	1787	1787	1787	1787
Ultra-supercritical	0	0	0	0	0	0
AUSC	0	0	0	0	0	0

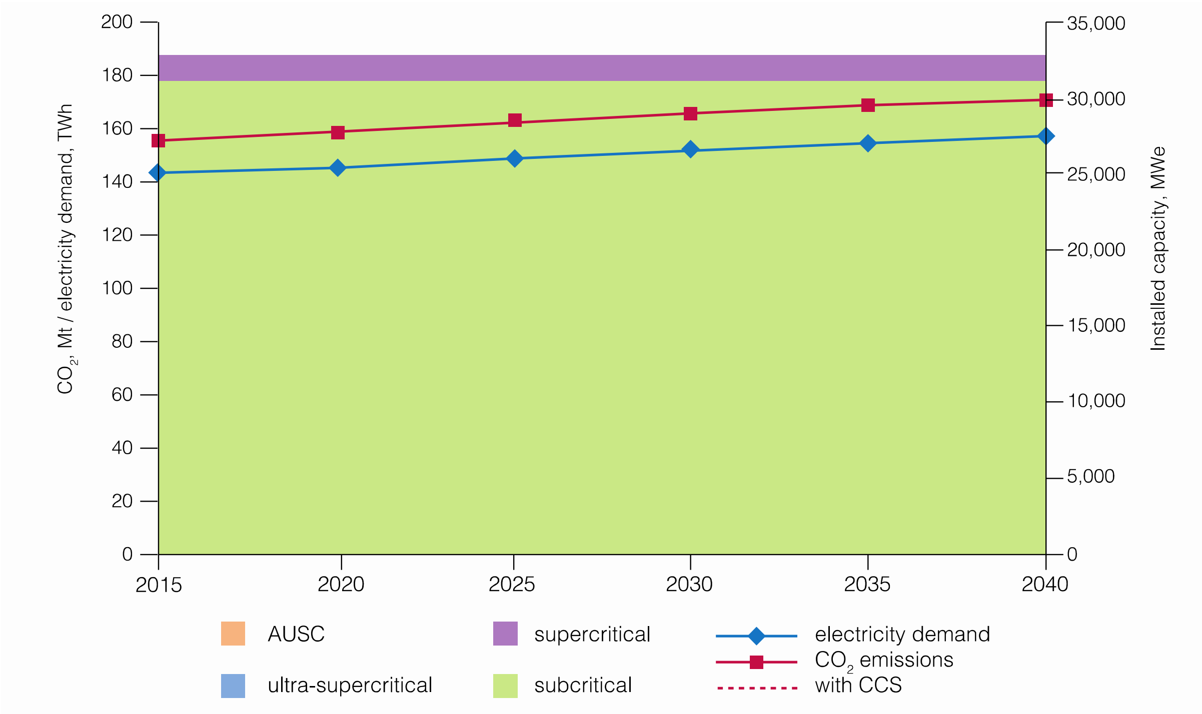

Figure 30 Polish base case scenario 2015-40

Table 26 Summary of Polish 50-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	143	146	148	151	154	157
CO_2 emissions (Mt)	156	159	161	134	137	129
Coal fleet profile (MWe)						
Subcritical	31052	24090	24090	11676	11676	4509
Supercritical	1787	1787	1787	1787	1787	1787
Ultra-supercritical	0	0	0	11200	11600	15800
AUSC	0	0	0	0	0	0

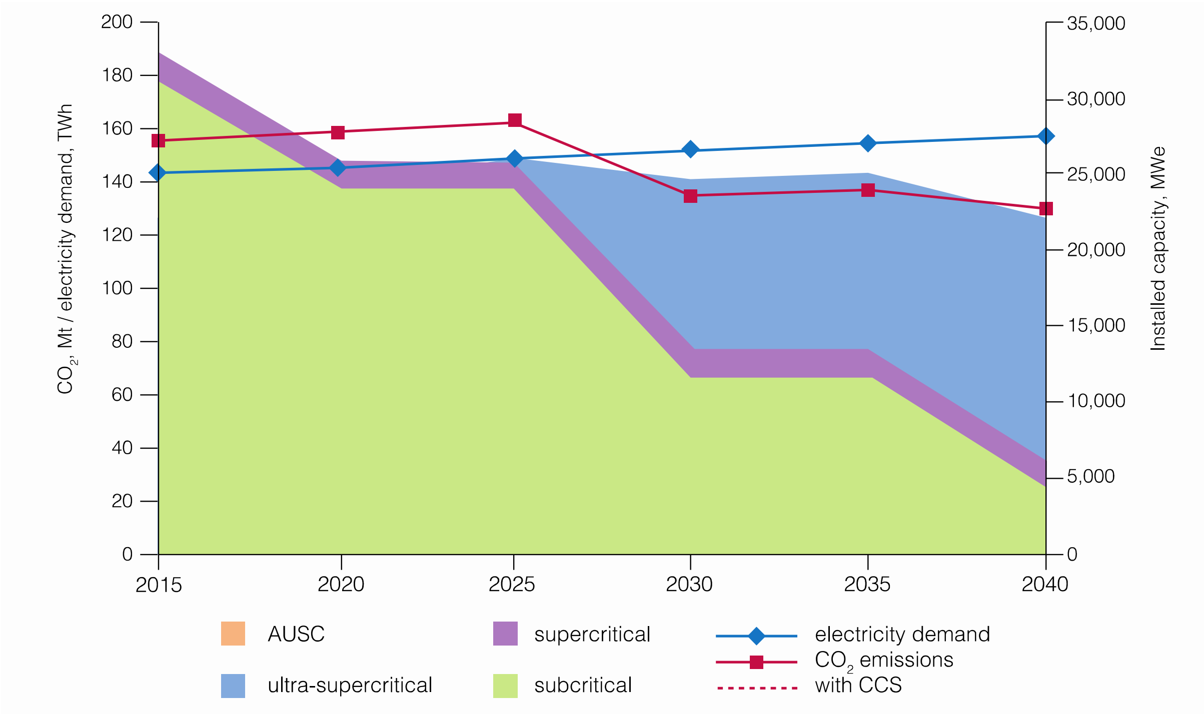

Figure 31 Polish 50-year retirement scenario 2015-40

Table 27 Summary of Polish 25-year retirement scenario 2015-40

	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	143	146	148	151	154	157
CO_2 emissions (Mt)	156	119	120	117	119	118
Coal fleet profile (MWe)						
Subcritical	31052	3106	3106	461	461	0
Supercritical	1787	1787	1787	1787	1787	0
Ultra-supercritical	0	15200	15400	15400	15400	15400
AUSC	0	0	0	1800	2200	4500

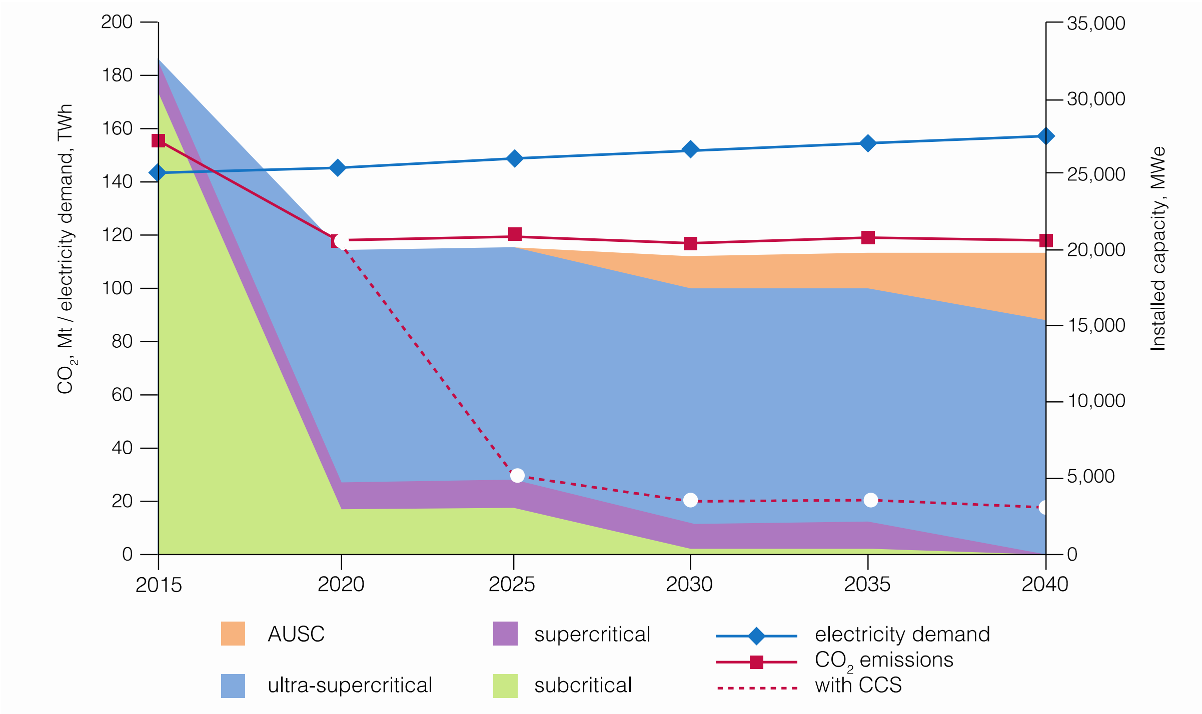

Figure 32 Polish 25-year retirement scenario 2015-40

The Polish situation contrasts well with the Japanese one in that demand in Poland shows a modest increase over the period of the study but is met initially (in the base case scenario) by a relatively old coal fleet where emissions rise from 156 Mt to 172 Mt (a 10% increase). Once new HELE capacity is introduced to replace the decommissioned older units under the 50-year scenario emissions of carbon dioxide fall markedly from 156 Mt in 2015 to 129 Mt in 2040 (a 17% reduction), despite increasing demand. Under the 25-year scenario, this effect is even more pronounced as AUSC units are commissioned in 2030 and emissions fall from 156 Mt to 118 Mt (a 24% reduction).

3.7 Russia

3.7.1 Profile of existing coal fleet

The Russian coal fleet accounts for approximately 3% of the global coal-fired capacity and is responsible for approximately 3% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010). The profile of the Russian coal fleet, abstracted from the WEPP is shown below in Table 28 and Figure 33. The majority of the coal plants are relatively old and Russia has the lowest share of power plants that larger than 300 MW capacity in the set of countries studied. Interestingly, the Russian coal fleet has a small number of very old ultra-supercritical power plants. These represent some of the very first units of this technology that were under development at that time.

Table 28 Russian coal-fired power plant by age and steam cycle conditions (MWe)				
Period	**All steam cycle conditions**	**Subcritical**	**Supercritical**	**Ultra-supercritical**
Pre–1940	52	52	0	0
1940–49	134	134	0	0
1950–59	3126	3126	0	0
1960–69	12815	7615	4300	600
1970–79	14334	7334	7000	0
1980–89	10272	8892	1380	0
1990–94	2390	1590	800	0
1995–99	995	995	0	0
2000–04	809	809	0	0
2005–09	942	302	640	0
2010–13	3138	1538	1600	0
Subtotal less planned	49007	32387	15720	600
Planned or under construction post-2013	1872	82	1790	0
Total	50879	32469	17510	600

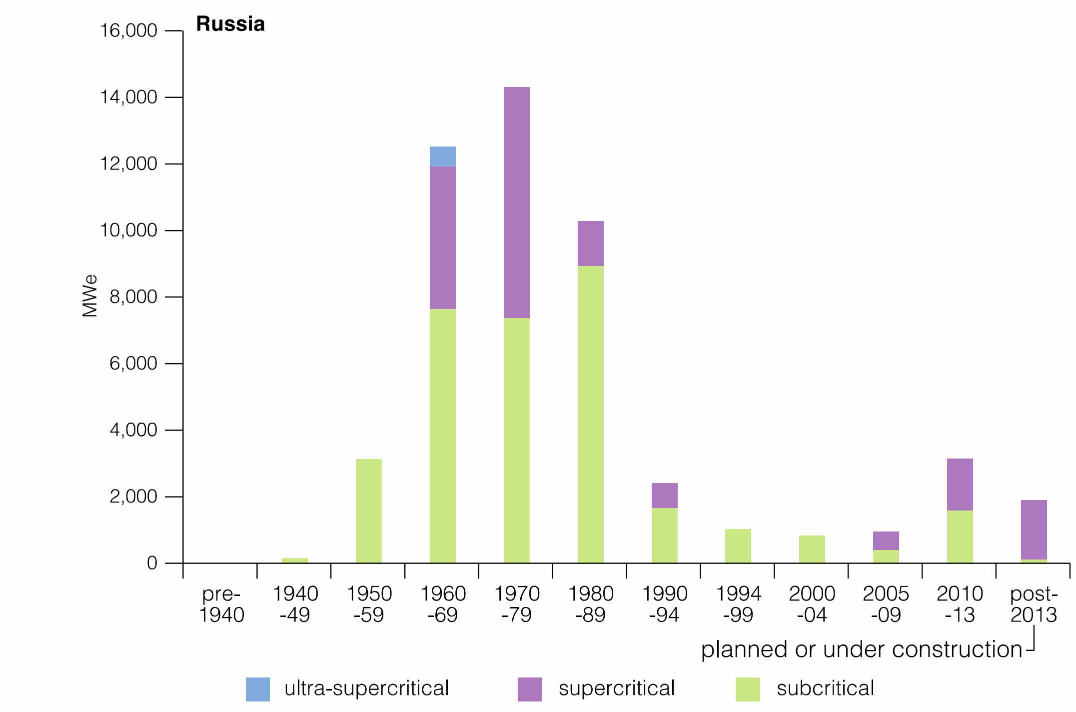

Figure 33 Russian coal-fired power plant by age and steam cycle conditions

3.7.2 Regional influences on future energy demand

In 2010 the Ministry of Energy of the Russian Federation published its Energy Policy to 2030 with the objective of maximising the effective use of natural energy resources and the potential of the energy sector to sustain economic growth, improve the quality of life of the population and promote strengthening of Russia's economic standing in the world. The Strategy determines objectives and goals of the Russian energy sector's long-term development over this period, its priorities and guidelines, as well as mechanisms of the state energy policy for its implementation.

Russia holds the second place in terms of coal reserves in the world (19% of the world reserves), the fifth place in terms of annual production (5% of the world production) and also accounts for approximately 12% of the world thermal coal trade and coal is seen as of continuing importance to the country. Primary energy sources are very important to the Russian economy, with more than 60% of Russian GDP based on oil, gas, and other extractive industries but a number of disputes over supply and payment are straining the dependence on such a limited economic base. As the world's largest country, energy policy in Russia has a strong regional dimension with different priorities for European, Siberian and Far Eastern provinces. In the European area, the maximum of nuclear power plants development, the replacement of steam power turbines by combined cycle units, and the development of new coal-fired power thermal plants in the Urals region are seen as priorities. In Siberia, coal-fired thermal power plants and hydro energy developments are highlighted while in the Far East hydro power plants, coal- fired thermal power plants and (in some regions) nuclear power plants are seen as priority areas.

3.7.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 29, 30 and 31 and Figures 34, 35 and 36 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 29 Summary of Russian base case scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	185	223	240	246	248	248
CO_2 emissions (Mt)	220	265	277	282	283	283
Coal fleet profile (MWe)						
Subcritical	32387	32387	32387	32387	32387	32387
Supercritical	15720	15720	15720	15720	15720	15720
Ultra-supercritical	600	600	2700	3500	3700	3700
AUSC	0	0	0	0	0	0

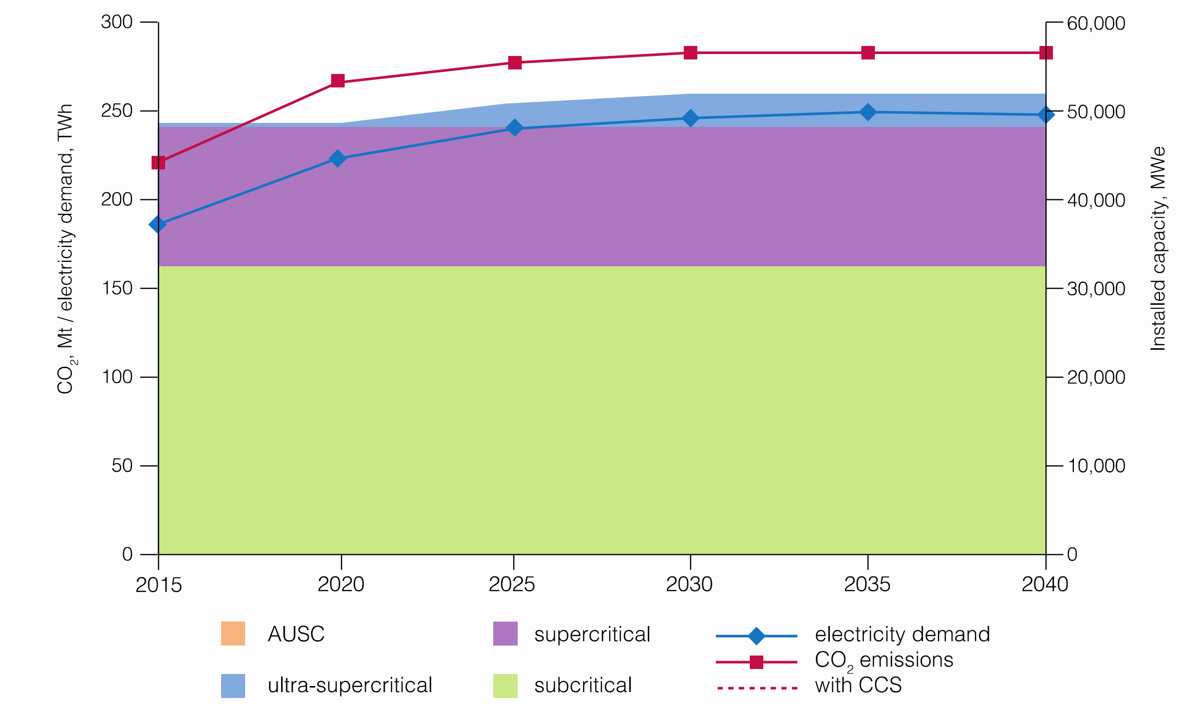

Figure 34 Russian base case scenario 2015-40

Table 30 Summary of Russian 50-year retirement scenario 2015-40

	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	185	223	240	246	248	248
CO_2 emissions (Mt)	220	246	263	258	260	252
Coal fleet profile (MWe)						
Subcritical	32387	21460	21460	14126	14126	5234
Supercritical	15720	11420	11420	4420	4420	3040
Ultra-supercritical	600	12600	14800	22600	22800	27500
AUSC	0	0	0	0	0	0

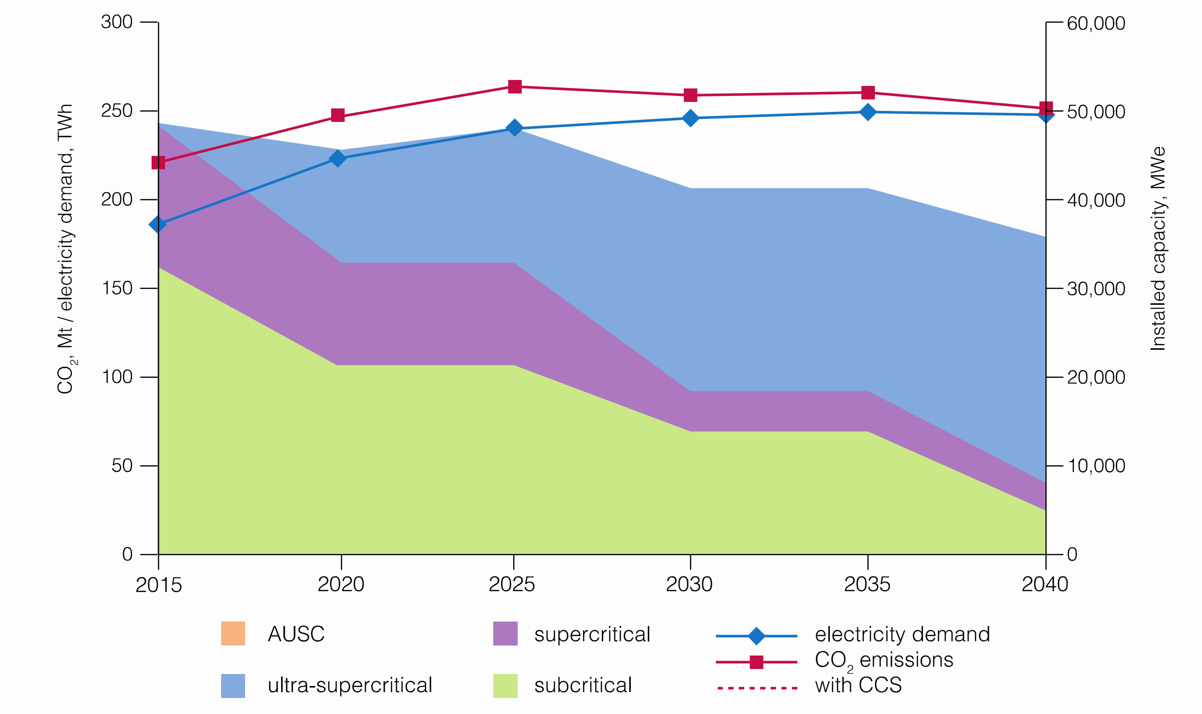

Figure 35 Russian 50-year retirement scenario 2015-40

Table 31 Summary of Russian 25-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	185	223	240	246	248	248
CO_2 emissions (Mt)	220	182	195	196	197	189
Coal fleet profile (MWe)						
Subcritical	32387	3644	3644	1840	1840	0
Supercritical	15720	2240	2240	2240	2240	0
Ultra-supercritical	600	25500	27600	27600	27600	27600
AUSC	0	0	0	1600	1800	3800

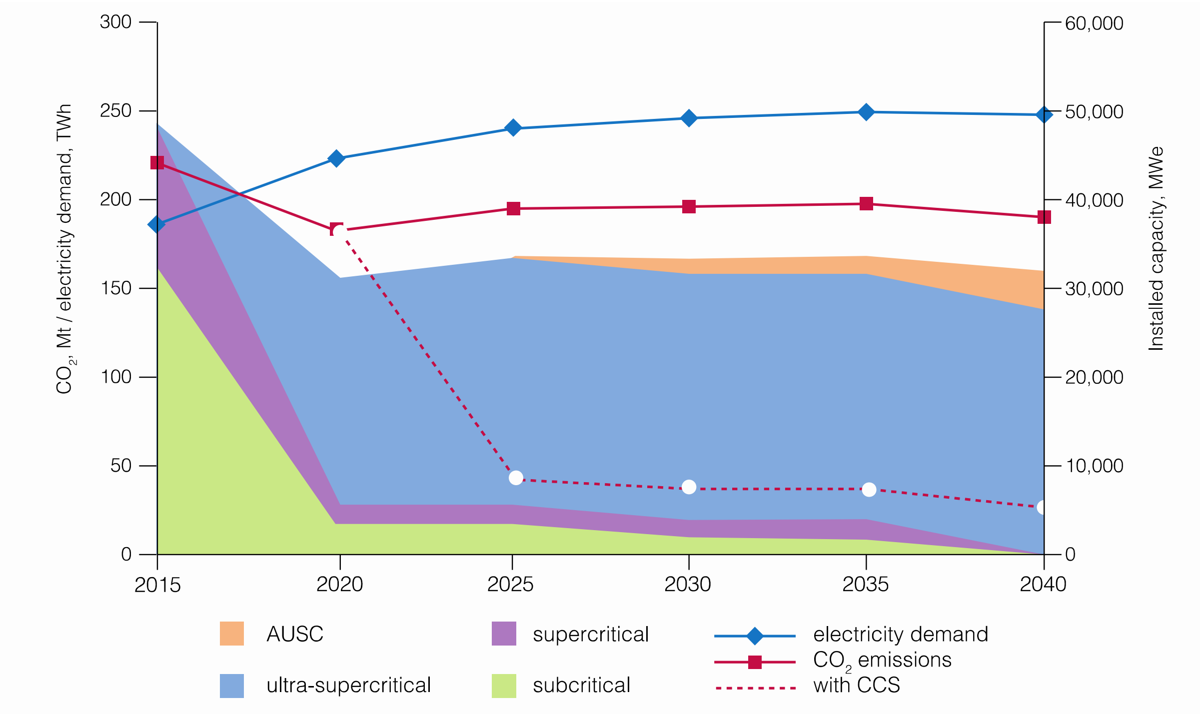

Figure 36 Russian 25-year retirement scenario 2015-40

The prospects for growth in coal-generated electricity are regarded as relatively good for Russia, as compared to its European neighbours. This is reflected in the increase in carbon dioxide emissions over the period of the study in the base case (2015-40) from 220 Mt to 283 Mt (a 29% increase). As with Poland, the relatively mature coal fleet results in a significant replacement of old capacity early in the timeline for the 50-year scenario which limits the rise in emissions from 220 Mt in 2015 to 252 Mt in 2040 (an increase of 15%). When AUSC HELE capacity is introduced, emissions fall from 2035 onwards, despite an increase in demand; 220 Mt to 189 Mt (a *decrease* of 14%).

3.8 South Africa

3.8.1 Profile of existing coal fleet

The South African coal fleet accounts for approximately 2% of the global coal-fired capacity and is responsible for approximately 2% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010). The vast majority of the units are of subcritical design, with supercritical units planned for the near future. The profile of the South African coal fleet, abstracted from the WEPP is shown below in Table 32 and Figure 37. Plant units are grouped by age and by steam cycle conditions (subcritical, supercritical and ultra-supercritical).

Table 32 South African coal-fired power plant by age and steam cycle conditions (MWe)				
Period	**All steam cycle conditions**	**Subcritical**	**Supercritical**	**Ultra-supercritical**
Pre–1940	0	0	0	0
1940–49	0	0	0	0
1950–59	347	347	0	0
1960–69	2783	2783	0	0
1970–79	9160	9160	0	0
1980–89	16252	16252	0	0
1990–94	5301	5301	0	0
1995–99	2709	2709	0	0
2000–04	1426	1426	0	0
2005–09	18	18	0	0
2010–13	3179	0	3179	0
Subtotal less planned	**41174**	**37995**	**3179**	**0**
Planned or under construction post-2013	8445	317	6358	0
Total	49620	38312	9538	0

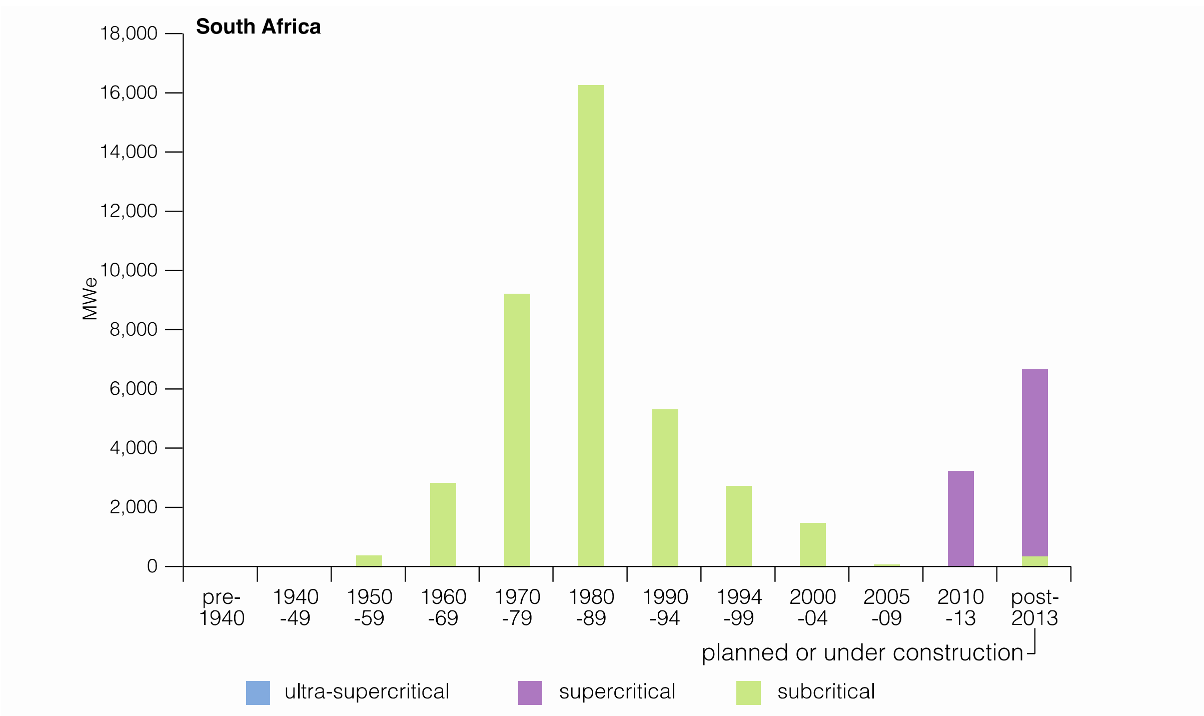

Figure 37 South African coal-fired power plant by age and steam cycle conditions

3.8.2 Regional influences on future energy demand

The South African government published its Integrated Resource Plan for Electricity 2010–30 in 2010 (South African Government) and a comprehensive update in 2013. The update reflects the country's ambitious economic growth aspirations set out in the National Development Plan so that unemployment and poverty in South Africa may be reduced. Significantly, the growth rate targeted (an average of 5.4% per year until 2030) is aligned with a shift in economic development away from energy intensive industries which would have the effect of dramatically reducing the electricity intensity of the economy. However, this makes the decision to build new capacity difficult as demand may not reach the levels required (especially not in the next five years) which raises the risk of overbuilding generation capacity to meet the target.

Apart from the uncertainty regarding the future demand, there are additional variables in the energy sector, specifically the potential for shale gas development, the extent of other gas developments in the region, the global agenda to combat climate change and the resulting mitigation requirements on South Africa, as well as the uncertainty in the cost of nuclear capacity and future fuel costs (specifically coal and gas), including fuel availability.

In all scenarios examined in the policy document, there is a requirement for new coal-fired generation between 2020 and 2025. The common element is the option for a regional coal project (of the order of 1200 MW) which is preferred to all other coal options because it is expected that the emissions from the generation will not count to the South African total in a future global emission targeting regime. If this is not the case, then there is no preference between a local and regional coal option.

The first major decision point for other coal-fired capacity is during 2014. If total net sent-out exceeds 265 TWh in 2013 then a procurement process is required to construct 1000 MW of capacity between 2020 and 2025. This is an early indication of a high growth trajectory which would require new capacity by 2021. It is recommended that procurement for additional capacity is launched during 2017 if total net sent-out exceeds 280 TWh (except if regional hydro is being pursued).

The significance of the life extension of plant (lifex) decision is highlighted in the documents. If the life extension decision is removed then an additional 9750 MW of pulverised coal-generation is required between 2029 and 2035. Amongst the additional options considered that include lifex a number of cases propose new PC coal generation capacity but only after 2031. It is only in the case of high coal costs, large shale gas exploitation and the Advanced Decline carbon mitigation scenario that there is no requirement for new large-scale domestic coal-fired generation before 2035.

3.8.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 33, 34 and 35 and Figures 38, 39 and 40 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 33 Summary of South African base case scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	274	316	359	385	405	437
CO_2 emissions (Mt)	275	308	342	361	377	402
Coal fleet profile (MWe)						
Subcritical	37995	37995	37995	37995	37995	37995
Supercritical	3179	3179	3179	3179	3179	3179
Ultra-supercritical	0	5400	10900	14100	16700	20700
AUSC	0	0	0	0	0	0

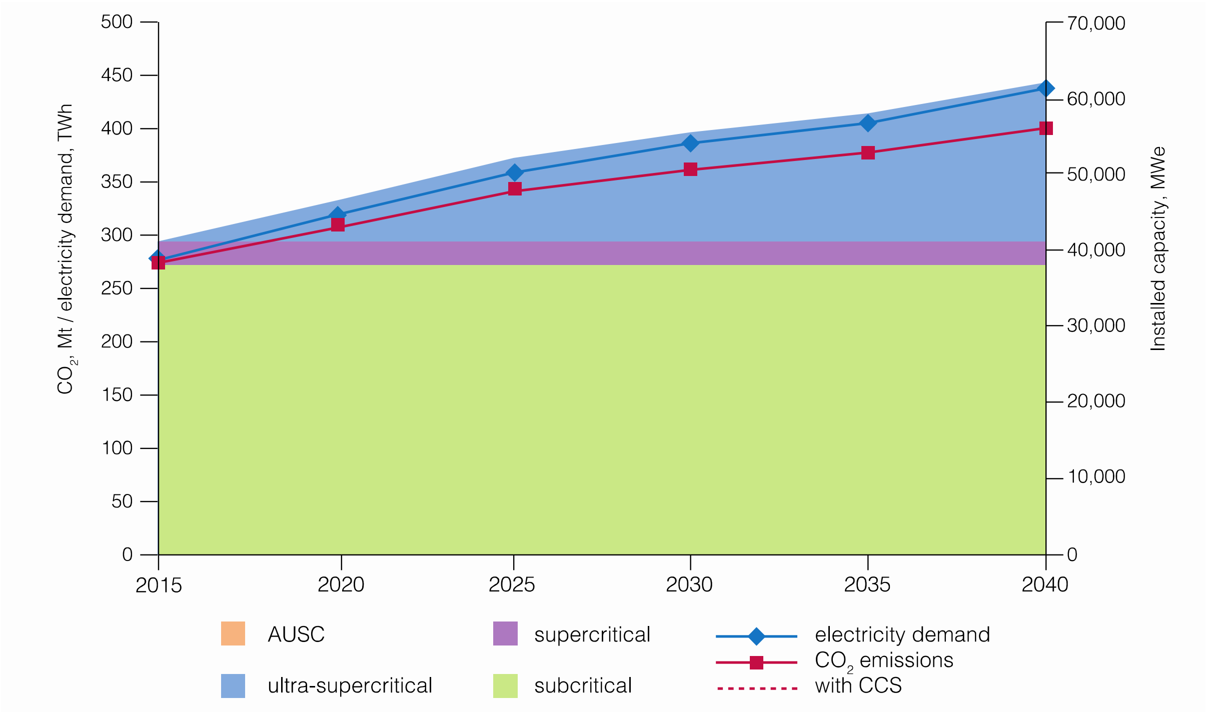

Figure 38 South African base case scenario 2015-40

Table 34 Summary of South African 50-year retirement scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	274	316	359	385	405	437
CO_2 emissions (Mt)	275	303	337	342	357	356
Coal fleet profile (MWe)						
Subcritical	37995	34866	34866	25706	25706	9454
Supercritical	3179	3179	3179	3179	3179	3179
Ultra-supercritical	0	8000	13500	24400	26900	44500
AUSC	0	0	0	0	0	0

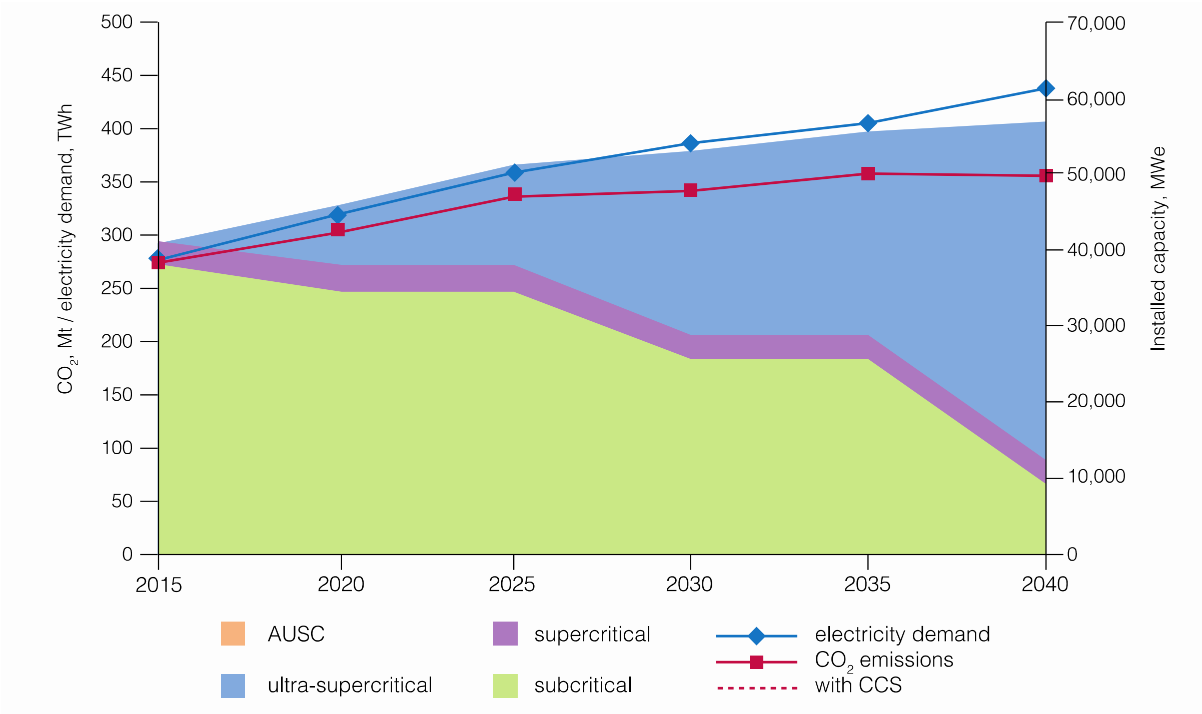

Figure 39 South African 50-year retirement scenario 2015-40

Table 35 Summary of South African 25-year retirement scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	274	316	359	385	405	437
CO_2 emissions (Mt)	275	254	287	295	309	325
Coal fleet profile (MWe)						
Subcritical	37995	4153	4153	18	18	0
Supercritical	3179	3179	3179	3179	3179	0
Ultra-supercritical	0	33600	39000	39000	39000	39000
AUSC	0	0	0	6800	9300	16400

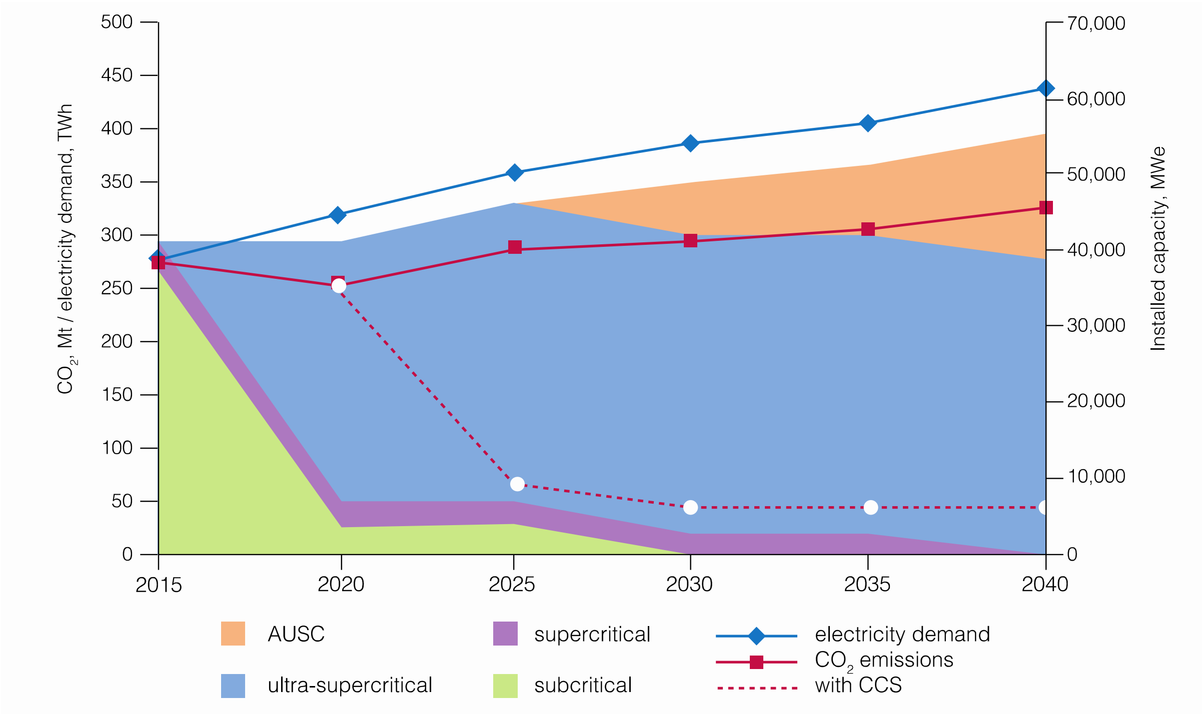

Figure 40 South African 25-year retirement scenario 2015-40

The South African situation is characterised by a shortfall in power illustrated by the immediate requirement for new capacity even in the base case. The healthy growth predicted for South African coal-based electricity is accompanied by a corresponding growth in carbon dioxide emissions over all scenarios, but as HELE capacity is introduced to replace older plant the emissions trend line begins to flatten. The base case is characterised by an increase from 275 Mt in 2015 to 402 Mt in 2040 (an increase of 46%). Under the 50-year scenario, older plant is retired at each of the review points and the introduction of replacement higher efficiency plant limits the increase in emissions; 275 Mt in 2015 to 356 Mt in 2040 (an increase of 29%). Under the 25-year scenario, the introduction of AUSC plant further limits emissions from 275 Mt to 325 Mt (an increase of 18%).

3.9 South Korea

3.9.1 Profile of existing coal fleet

Among the ten countries with the largest coal-fired power generation worldwide, the fleet in Korea has one of the largest shares of supercritical or ultra-supercritical coal power generation in a single country. In addition, it is among the three countries with the youngest installed fleet and the largest share of large generation units that is currently operating. The profile of the South Korean coal fleet, abstracted from the WEPP is shown below in Table 36 and Figure 41. The South Korean coal fleet accounts for approximately 2% of the global coal-fired capacity and is responsible for approximately 2% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010).

Table 36 South Korean coal-fired power plant by age and steam cycle conditions (MWe)				
Period	**All steam cycle conditions**	**Subcritical**	**Supercritical**	**Ultra-supercritical**
Pre–1940	0	0	0	0
1940–49	0	0	0	0
1950–59	0	0	0	0
1960–69	80	80	0	0
1970–79	1520	1520	0	0
1980–89	2613	2613	0	0
1990–94	2360	860	1500	0
1995–99	7836	1336	6500	0
2000–04	4642	42	4600	0
2005–09	6915	0	0	6915
2010–13	738	738	0	0
Subtotal less planned	**26705**	**7190**	**12600**	**6915**
Planned or under construction post-2013	13240	300	1840	10100
Total	**39945**	**7490**	**14440**	**17015**

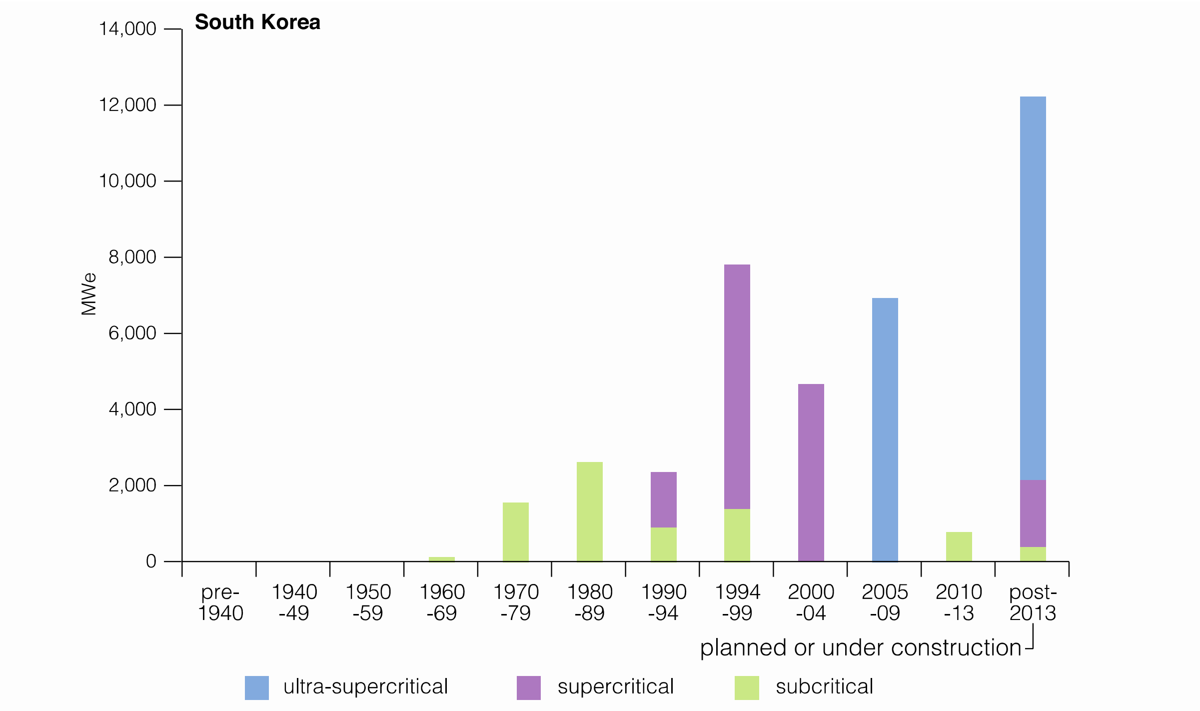

Figure 41 South Korean coal-fired power plant by age and steam cycle conditions

3.9.2 Regional influences on future energy demand

South Korea is an energy-intensive nation. It is the world's eleventh highest in terms of energy consumption and is the fifth-largest oil importer. Energy and environmental policies focus on low-carbon and green growth and on creating a momentum for economic growth by means of green technology and clean energy. In 2008, Low Carbon, Green Growth was proclaimed by President Lee Myung-bak as a national vision to guide the nation's long-term development. Korea has made efforts to enhance energy security by taking measures to diversify energy sources, reduce the use of fossil fuels and foster the development of renewable energy. The contribution of renewable sources to total primary energy supply (TPES) in Korea is the lowest in the OECD. To address this anomaly, the government has established an 11% target of new and renewable energy in TPES by 2030. A notable feature of Korea energy policy is the value it places on research and development. Government expenditure on energy-related research, development and deployment (RD&D) has increased significantly over the past decade and is now among the highest in the OECD. Investment in energy-related RD&D was over 600 billion Korean won (KRW) in 2010. In the longer term, there is considerable interest in investigating shale gas possibilities for Korea and the government and private industry have been actively entering into partnerships with interested stakeholders.

3.9.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 37, 38 and 39 and Figures 42, 43 and 44 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 37 Summary of South Korean base case scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	198	194	199	194	210	223
CO_2 emissions (Mt)	167	163	168	164	176	186
Coal fleet profile (MWe)						
Subcritical	7190	7190	7190	7190	7190	7190
Supercritical	12600	12600	12600	12600	12600	12600
Ultra-supercritical	6915	6915	6915	6915	8900	10500
AUSC	0	0	0	0	0	0

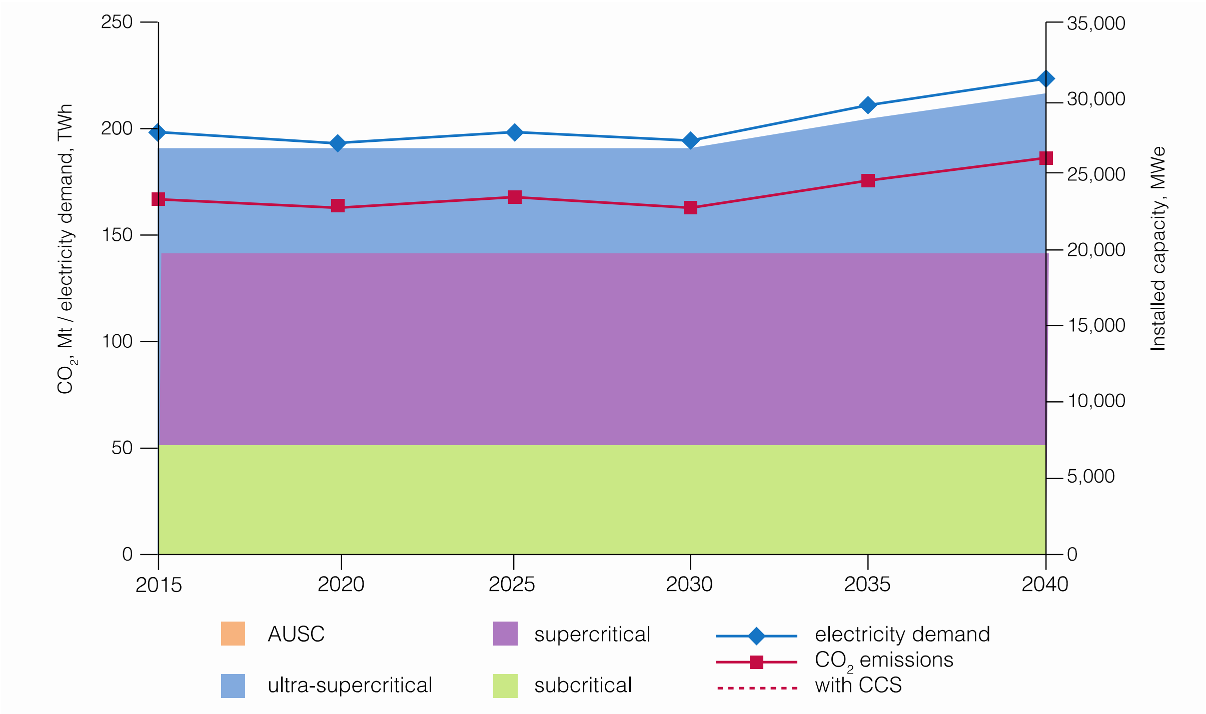

Figure 42 South Korean base case scenario 2015-40

Table 38 Summary of South Korean 50-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	198	194	199	194	210	223
CO_2 emissions (Mt)	167	163	168	162	175	182
Coal fleet profile (MWe)						
Subcritical	7190	7110	7110	5590	5590	2977
Supercritical	12600	12600	12600	12600	12600	12600
Ultra-supercritical	6915	6915	6915	7600	9700	13700
AUSC	0	0	0	0	0	0

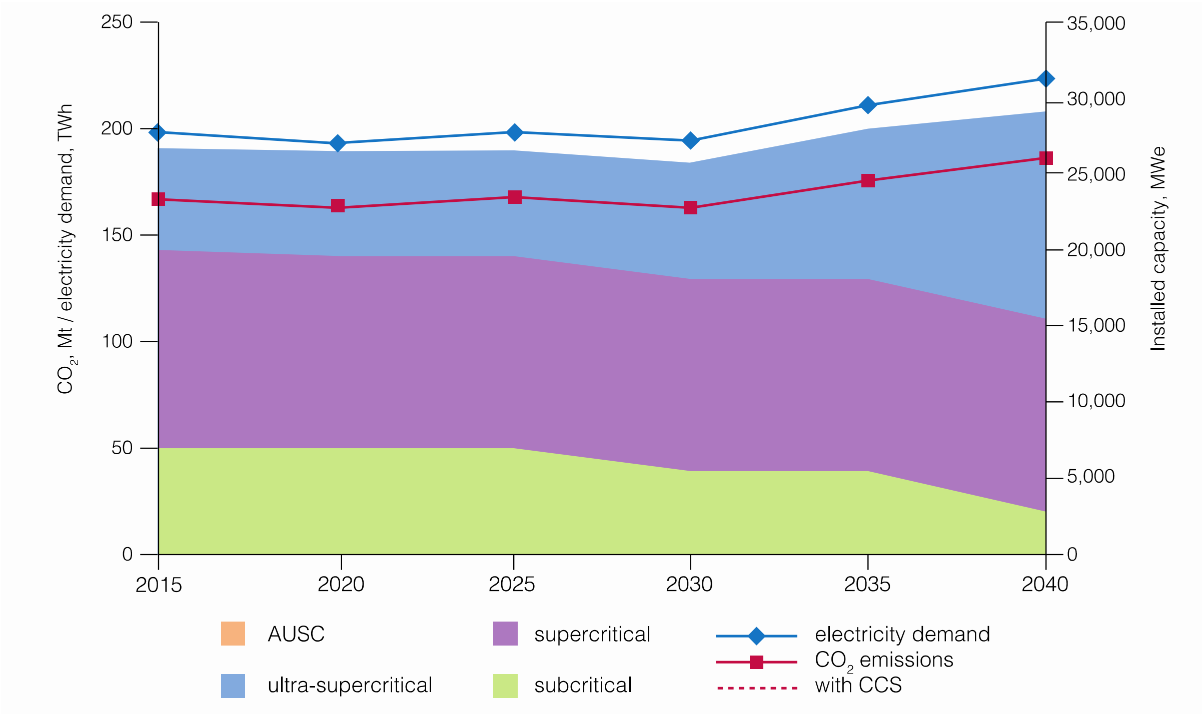

Figure 43 South Korean 50-year retirement scenario 2015-40

Table 39 Summary of South Korean 25-year retirement scenario 2015-40

	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	198	194	199	194	210	223
CO_2 emissions (Mt)	167	158	162	142	153	154
Coal fleet profile (MWe)						
Subcritical	7190	2116	2116	728	728	0
Supercritical	12600	11100	11100	0	0	0
Ultra-supercritical	6915	12300	12900	12900	12900	5985
AUSC	0	0	0	11000	13100	22300

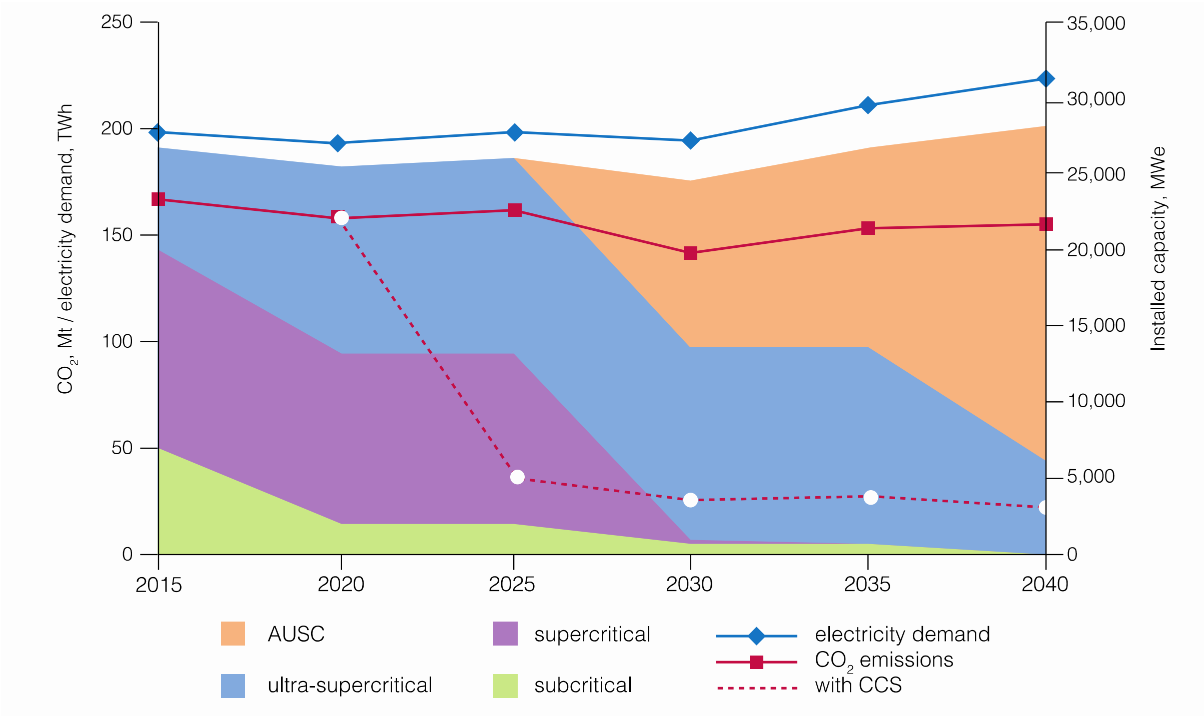

Figure 44 South Korean 25-year retirement scenario 2015-40

South Korea shares the characteristic with other newly developed countries in having a relatively young, high efficiency (HELE) coal fleet in place. Emissions trends follow the demand growth under the base case scenario rising from 167 Mt to 186 Mt (an increase of 11%). Despite some plant replacement in the 50-year scenario, the impact is less marked than for the cases of countries such as Russia and Poland with much older fleets and emissions rise from 167 Mt to 182 Mt (a 9% increase). Finally under the 25-year scenario the replacement of supercritical plant by AUSC plant limits the growth in emissions from 167 Mt in 2015 to 154 Mt in 2040 (an increase of 7%).

3.10 USA

3.10.1 Profile of existing coal fleet

The coal-fired power plant fleet in the USA is the second largest installed in a single country after China. Among the ten countries with the largest coal power generation capacity worldwide, the United States has the lowest share of power plants that are younger than 20 years old. The share of power generation units with a capacity above 300 MW is however comparatively high. The profile of the US coal fleet, abstracted from the WEPP is shown below in Table 40 and Figure 45. The US coal fleet accounts for approximately 21% of the global coal-fired capacity and is responsible for approximately 23% of global carbon dioxide emissions from coal through the production of electricity (IEA, 2010). Like Russia, the US fleet profile includes some of the very first supercritical units.

Table 40 USA coal-fired power plant by age and steam cycle conditions (MWe)				
Period	**All steam cycle conditions**	**Subcritical**	**Supercritical**	**Ultra-supercritical**
Pre–1940	103	103	0	0
1940–49	1186	1186	0	0
1950–59	39064	39064	0	0
1960–69	63665	44528	12673	0
1970–79	120518	63676	56823	0
1980–89	79458	72197	7236	0
1990–94	8192	10445	1426	0
1995–99	3692	3692	0	0
2000–04	3040	3030	0	0
2005–09	7526	5161	2355	0
2010–13	13484	3750	8990	672
Subtotal less planned	**339927**	**246832**	**89503**	**672**
Planned or under construction post-2013	12990	2208	4026	1250
Total	**352917**	**249040**	**93529**	**1922**

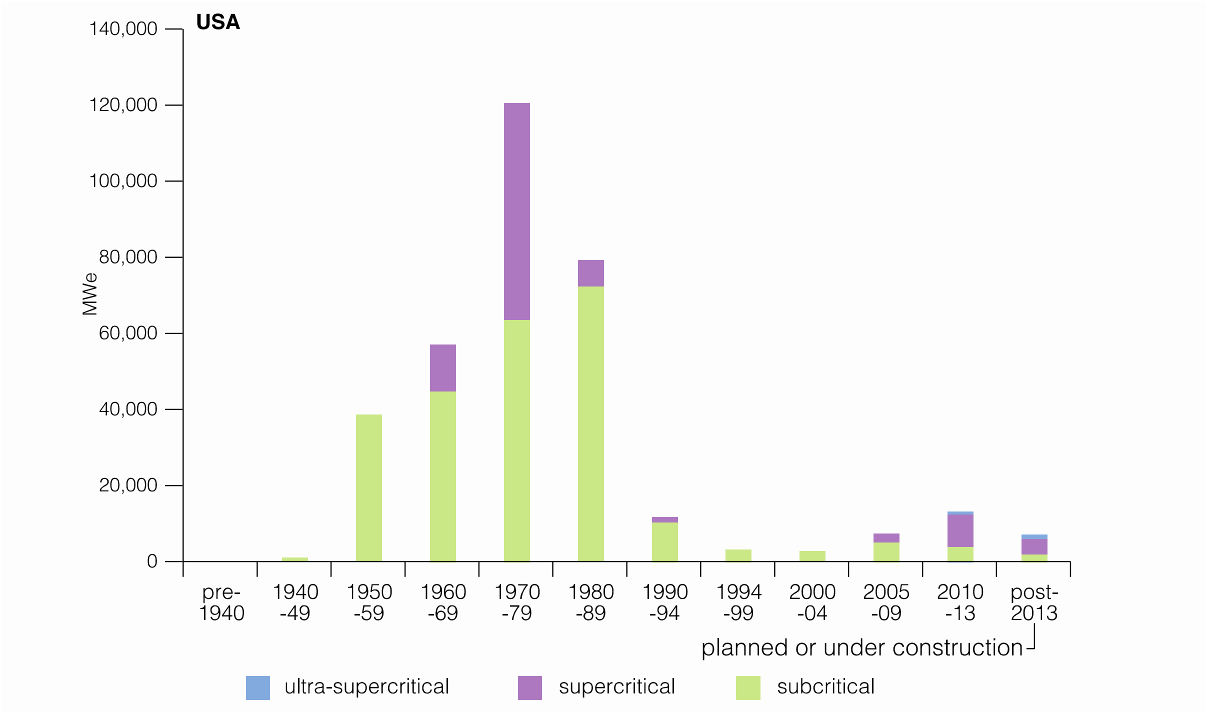

Figure 45 USA coal-fired power plant by age and steam cycle conditions

3.10.2 Regional influences on future energy demand

US energy policy is framed by the 'Blueprint for a secure energy future' issued by Presidential decree in March 2011 (US Government Whitehouse Information Service, 2011) and currently under revision. The policy sets out aims and objectives under three main headings:

Develop and Secure USA's Energy Supplies

- Expand Safe and Responsible Domestic Oil and Gas Development and Production
- Lead the World Towards Safer, Cleaner, and More Secure Energy Supplies

Provide Consumers with Choices to Reduce Costs and Save Energy

- Reduce Consumer Costs at the Pump with More Efficient Cars and Trucks
- Cut Energy Bills with More Efficient Homes and Buildings

Innovate Our Way to a Clean Energy Future

- Harness USA's Clean Energy Potential
- Win the future through Clean Energy Research and Development
- Lead by Example: The Federal Government and Clean Energy

The US has set itself a target of generating 80 % of electricity from a mix of clean energy sources including renewable energy sources like wind, solar, biomass, and hydropower; nuclear power; efficient natural gas; and clean coal by 2035. Natural gas is a very significant fuel to the future of US energy supply following the recent initiative of exploiting shale. Considering the implications of the 'shale gas revolution', BP (2014) note that the US is likely to become a natural gas exporter in the not-so-distant future and already total oil imports have been cut by almost half. The replacement of coal-fired plant by natural gas-fired plant is gathering momentum and as a consequence reducing emissions of carbon dioxide (natural gas fired power generation has about half the emissions of coal fired generation).

3.10.3 Future coal-based electricity demand

The predicted growth in coal-based electricity generation, the concomitant emissions of carbon dioxide and the composition of the coal fleet by steam cycle conditions are summarised below in Tables 41, 42 and 43 and Figures 46, 47 and 48 for the three scenarios: base case, 50-year retirement scenario and 25-year retirement scenario.

Table 41 Summary of USA base case scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	1614	1656	1727	1767	1807	1829
CO_2 emissions (Mt)	1482	1523	1585	1627	1669	1767
Coal fleet profile (MWe)						
Subcritical	246832	246832	246832	246832	246832	246832
Supercritical	89503	89503	89503	89503	89503	89503
Ultra-supercritical	672	672	672	672	672	672
AUSC	0	0	0	0	0	0

Figure 46 USA base case scenario 2015-40

Table 42 Summary of USA 50-year retirement scenario 2015-40

	2015	2020	2025	2030	2035	2040
Electricity demand (TWh)	1614	1656	1727	1767	1807	1829
CO_2 emissions (Mt)	1482	1441	1496	1456	1486	1445
Coal fleet profile (MWe)						
Subcritical	246832	161951	161951	98275	98275	26079
Supercritical	89503	76830	76830	20007	20007	12771
Ultra-supercritical	672	62000	71000	155000	160000	208000
AUSC	0	0	0	0	0	0

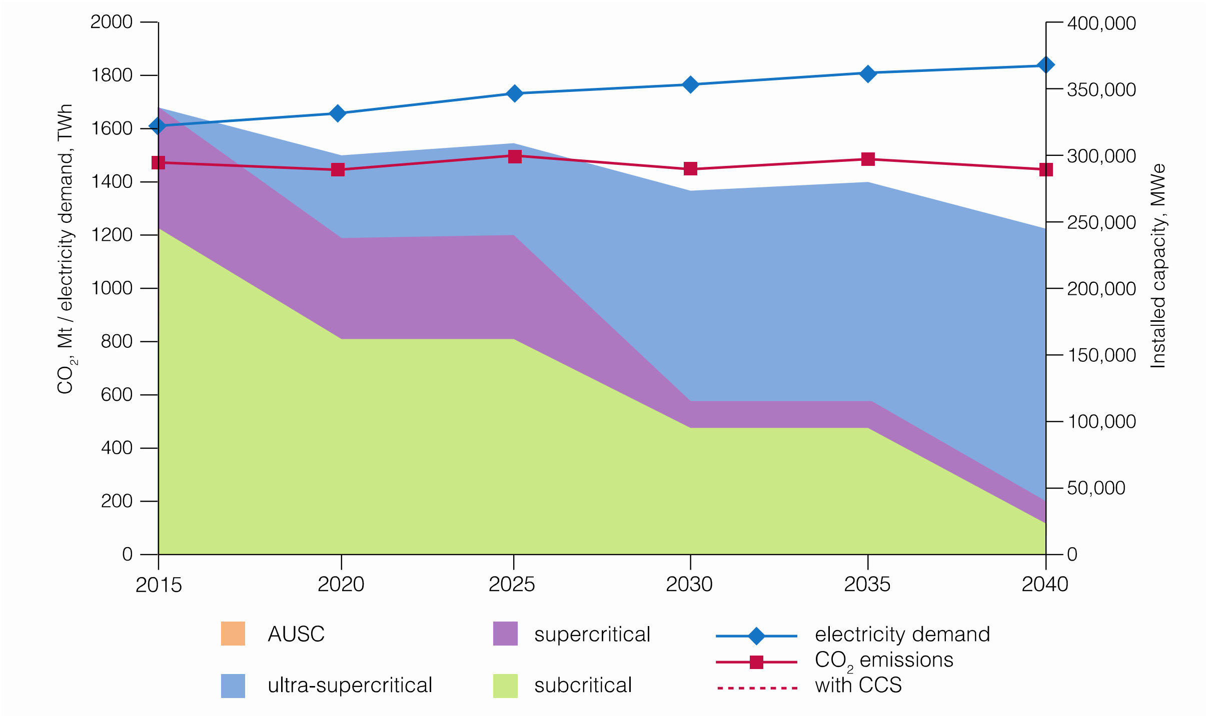

Figure 47 USA 50-year retirement scenario 2015-40

Table 43 Summary of USA 25-year retirement scenario 2015-40						
	2015	**2020**	**2025**	**2030**	**2035**	**2040**
Electricity demand (TWh)	1614	1656	1727	1767	1807	1829
CO_2 emissions (Mt)	1482	1268	1301	1366	1389	1384
Coal fleet profile (MWe)						
Subcritical	246832	15633	15633	8912	8912	0
Supercritical	89503	11345	11345	11345	11345	0
Ultra-supercritical	672	187300	192700	192700	192700	192700
AUSC	0	0	0	17600	22000	39000

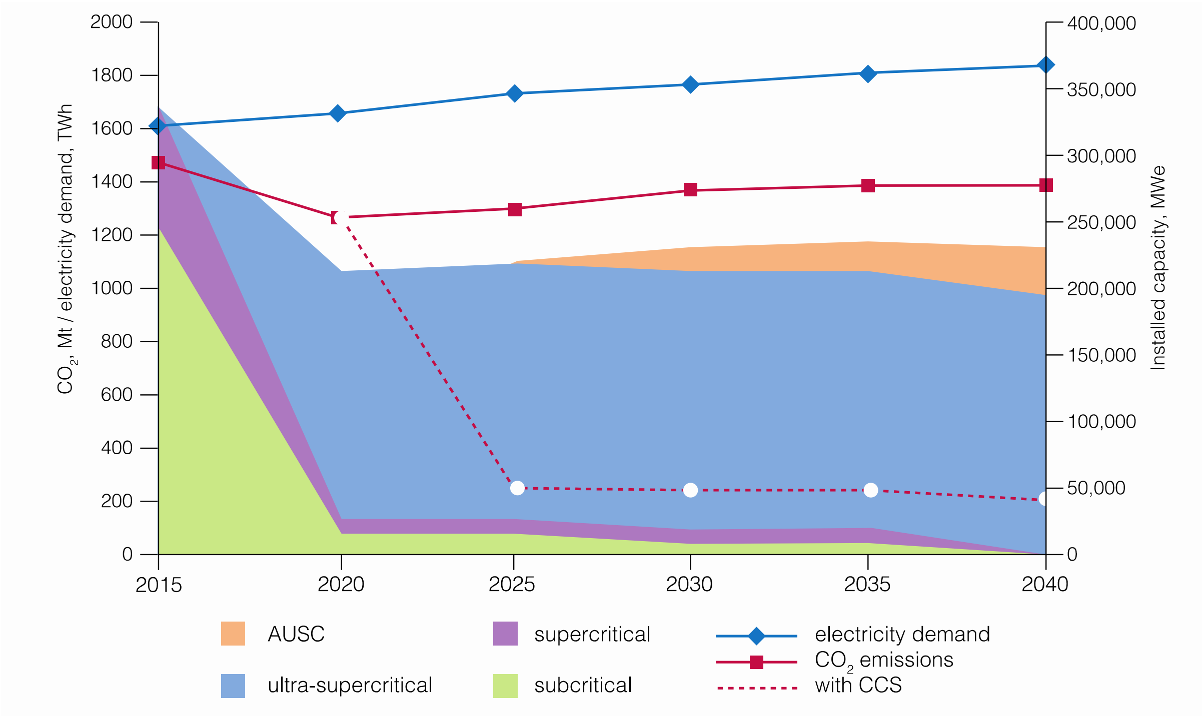

Figure 48 USA 25-year retirement scenario 2015-40

With modest growth predicted for coal generated electricity in the US, an upwards trend on carbon dioxide emissions follows under the base case scenario from 1482 Mt in 2015 to 1767 Mt in 2040 (a 19% increase). In common with other OECD countries, a relatively old fleet profile results in the early retirement of less efficient plant in the two upgrade scenarios leading to falls in carbon dioxide emissions despite the predicted growth in coal-fired electricity. For the 50-year scenario, emissions fall from 1482 Mt to 1445 Mt (a 2% reduction), despite increasing demand. Under the 25-year scenario, emissions fall further from 1482 Mt in 2015 to 1384 Mt in 2040 (a 7% reduction).

4 HELE and CCS deployment

4.1 CCS readiness

The CCS readiness of a coal fleet as a concept embraces a number of factors. These include the technology and age profile of the fleet, the availability of consented space upon which to establish carbon capture technology for individual units, the establishment of transport infrastructure to convey liquefied carbon dioxide and the availability of permitted storage capacity within an economically viable range of the power plant. Also, an individual country may have specific commitments to carbon abatement that mandate CCS retrofit at an earlier, or later, time than that suggested from technical analysis alone. These issues are most appropriately dealt with in the detailed individual country studies envisaged, but some general comments and trends may be taken from the present analysis.

It is, of course a truism that CCS fitted to *any* plant would give significant reductions in emissions of carbon dioxide but more realistically CCS retrofit to existing and new plant may be considered as viable only when higher efficiency steam cycles are involved (i.e. better than subcritical) and when the plant is relatively young, say less than ten years old. From a review of the three HELE development pathways studied in this report, the following comments may be made on CCS readiness prospects:

- Countries such as China, Japan and South Korea that have relatively young and efficient coal fleets would benefit from the early adoption of CCS to enhance the emissions savings that already being achieved through HELE technologies.
- Countries such as Poland and Russia with older and less efficient coal fleets would not benefit from CCS rollout until a significant tranche of capacity has been replaced with HELE plant. For these cases, this occurs around 2030, even under the 50-year retirement scenario.
- Countries such as the United States and India that have high levels of emissions in absolute terms would benefit from an early rollout of CCS. Where significant older capacity exists the benefits are enhanced once HELE plant begins to replace the older units.
- In all cases, the 25-year life scenario represents the best option for CCS deployment as all coal fleets transition to a high HELE content quickly and enjoy maximum carbon dioxide abatement as any remaining lower efficiency capacity is retired. This is particularly evident in the Indian case where the effects of a rapidly increasing demand for electricity and attenuated by a combination of HELE and CCS technologies.

4.2 Costs

According to Rong and Victor (2012), the capital cost of new power plants varies substantially across countries. Costs for most power generating technologies including both fossil fuel plants (eg advanced coal) and renewables (eg onshore wind) are much lower in some emerging Asian countries, particularly China. The cost to build a supercritical power plant in China, for example, is approximately one third of the corresponding cost of building a similar unit in the United States. Comparative plant construction costs for ten countries are given in Figure 49.

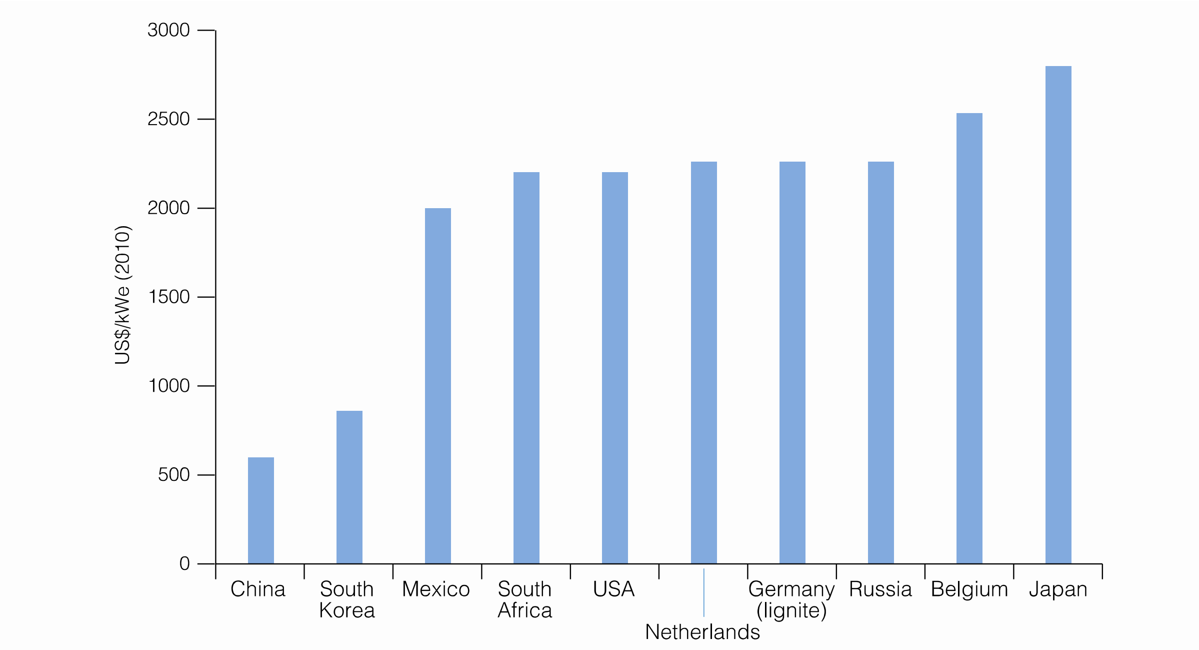

Figure 49 Overnight capex for building supercritical coal-fired plant in different countries (after Rong and Victor, 2012.)

These costs assume that the plants operate on baseload. These estimates highlight the increased expenditure associated with the higher specification materials used for steam tubing and other estimates put the overnight construction costs of a supercritical coal power plant in the US are reported as over 3000 US$/kW (EIA 2010).

In 2012 Black and Veatch published a comprehensive estimate of the relative costs of constructing various energy generation technologies. Pulverised coal fired plants were among the technologies modelled, with the option for incorporating CCS technology. The plant costs were based on a single reheat, condensing, tandem compound, four-flow steam turbine generator set, a single reheat supercritical steam generator and wet mechanical draft cooling tower, NOx control including an SCR unit, and air quality control equipment for particulate and SO_2 control, based on recently construction US plants. The plants net output was set at approximately 606 MWe.

The cost of constructing this plant was estimated at 2890 US$/kW +35% with a relatively high degree of confidence. Over the 40-year analysis period modelled, a 4% improvement in heat rate was assumed. The 2010 capital cost breakdown for the power plant is shown in Figure 50.

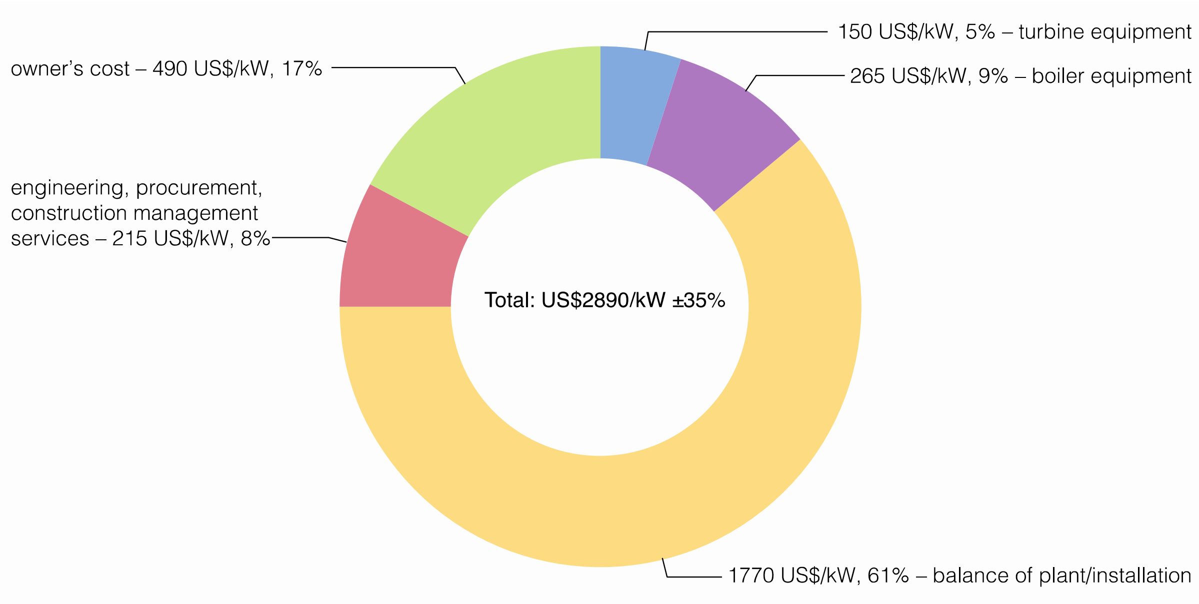

Figure 50 Capital cost breakdown for the construction of a 606 MWe pulverised coal fired plant 2010 data.

Modelling the plant described above, but incorporating CCS, the net output falls to approximately 455 MWe as a consequence of the performance impact and costs of operating the CCS plant. Assuming CCS technology based on 85% carbon dioxide removal and that this would be available after 2020, the 2020 plant capital cost was estimated at 6560 US$/kW –45% and +35%. The uncertainty in the plant cost is due to the uncertainty associated with the CCS technology.

EIA (2013) have recently updated their capital cost estimates for utility scale electricity generating plants to include PC plants fitted with CCS and other advanced cycles such as IGCC. The focus of the 2013 update was to gather current information on the 'overnight' construction costs, operating costs, and performance characteristics for a wide range of generating technologies. The estimates were developed through costing exercises, using a common methodology across technologies as comparing cost estimates developed on a similar basis using the same methodology is of particular importance to ensure modelling consistency.

Each coal power technology is represented by a generic facility of a specific size and configuration, in a location that does not have unusual constraints or infrastructure requirements. Where possible, costs estimates were based on information derived from actual or planned projects known to the consultant. When this information was not available, the project costs were estimated using costing models that account for the current labour and materials rates necessary to complete the construction of a generic facility as well as consistent assumptions for the contractual relationship between the project owner and the construction contractor.

The specific overnight costs for each type of facility were broken down to include:

- Civil and structural costs: allowance for site preparation, drainage, the installation of underground utilities, structural steel supply, and construction of buildings on the site.
- Mechanical equipment supply and installation: major equipment, including but not limited to, boilers, flue gas desulfurization scrubbers, cooling towers, steam turbine generators, condensers, photovoltaic modules, combustion turbines, and other auxiliary equipment.
- Electrical and instrumentation and control: electrical transformers, switchgear, motor control centres, switchyards, distributed control systems, and other electrical commodities.
- Project indirect costs: engineering, distributable labour and materials, craft labour overtime and incentives, scaffolding costs, construction management start up and commissioning, and fees for contingency, and
- Owners costs: development costs, preliminary feasibility and engineering studies, environmental studies and permitting, legal fees, insurance costs, property taxes during construction, and the electrical interconnection costs, including a tie-in to a nearby electrical transmission system.

The results are summarised in Table 44.

Table 44 Updated estimates of coal power plant capital and operating costs

	Plant characteristics			Plant costs (2012$)		
	Nominal capacity (MW)	Heat rate (Btu/kWh)		Overnight capital cost ($/kW)	Fixed O&M cost ($/kW-y)	Variable O&M cost ($/MWh)
Single unit advanced PC	650	8800		3246	37.80	4.47
Dual unit advanced PC	1300	8800		2934	31.18	4.47
Single unit advanced PC with CCS	650	12000		5227	80.53	9.51
Dual unit advanced PC with CCS	1300	12000		4724	66.43	9.51
Single unit IGCC	600	8700		4400	62.25	7.22
Dual unit IGCC	1200	8700		3784	51.39	7.22
Single unit IGCC with CCS	520	10700		6599	72.83	8.45

These costs are consistent with the Black and Veatch estimates for plant with, and without CCS, and so were used to prepare estimates for each country for the cost of installing additional HELE technology (where required) to meet predicted electricity-from-coal demand *without* CCS. Following on from this, the costs of providing the additional HELE plant to meet demand *and* to replace retired units were estimated. Finally, an estimate of the additional capacity required covering the shortfall that would result from CCS efficiency penalties and operating constraints was made. Each set of estimates was prepared for the cases of 2020 and 2040 coal-based generation under the 50-year retirement scenario to indicate the range of costs for CCS deployment. The results are presented in Tables 45 and 46.

Table 45 Estimated costs of HELE capacity upgrades with and without CCS (2020)

Country	HELE plant added to base case scenario (MWe)	Costs of added HELE plant without CCS (base case, US$ billion)	Costs of added HELE plant with CCS (base case, US$ billion)	HELE plant added in 50-year retirement scenario (MWe)	Costs of added HELE plant to 50-year retirement case without CCS (US$ billion)	Costs of added HELE plant to 50-year retirement case with CCS (US$ billion)	Additional capacity required from CCS derate to 50-year retirement scenario coal fleet (MWe)	Costs of additional capacity US$ billion
Australia	0	0.0	0.0	1900	5.6	9.0	475	2.2
China	0	0.0	0.0	92347	270.9	436.2	23087	109.1
Germany	0	0.0	0.0	0	0.0	0.0	0	0.0
India	0	0.0	0.0	0	0.0	0.0	0	0.0
Japan	0	0.0	0.0	1800	5.3	8.5	450	2.1
Poland	0	0.0	0.0	0	0.0	0.0	0	0.0
Russia	0	0.0	0.0	12000	35.2	56.7	3000	14.2
South Africa	5400	15.8	25.5	8000	23.5	37.8	2000	9.4
South Korea	0	0.0	0.0	0	0.0	0.0	0	0.0
USA	0	0.0	0.0	61328	179.9	289.7	15332	72.4
Base costs (US$/kW)								
Units without CCS	2934							
Units with CCS	4724							

Derate of 25% from CCS

Assume additional derate is also fitted with CCS

Table 46 Estimated costs of HELE capacity upgrades with and without CCS (2040 cumulative)

Country	HELE plant added to base case scenario (MWe)	Costs of added HELE plant without CCS (base case, US$ billion)	Costs of added HELE plant with CCS (base case, US$ billion)	HELE plant added in 50-year retirement scenario (MWe)	Costs of added HELE plant to 50-year retirement case without CCS (US$ billion)	Costs of added HELE plant to 50-year retirement case with CCS (US$ billion)	Additional capacity required from CCS derate to 50-year retirement scenario coal fleet (MWe)	Costs of additional capacity US$ billion
Australia	0	0.0	0.0	12500	36.7	59.1	3125	14.8
China	307347	901.8	1451.9	432347	1268.5	2042.4	108087	510.6
Germany	0	0.0	0.0	9171	26.9	43.3	2293	10.8
India	72000	211.2	340.1	119600	350.9	565.0	29900	141.2
Japan	0	0.0	0.0	4100	12.0	19.4	1025	4.8
Poland	0	0.0	0.0	15800	46.4	74.6	3950	18.7
Russia	3100	9.1	14.6	26900	78.9	127.1	6725	31.8
South Africa	20700	60.7	97.8	44500	130.6	210.2	11125	52.6
South Korea	3585	10.5	16.9	6785	19.9	32.1	1696	8.0
USA	0	0.0	0.0	246178	722.3	1162.9	61545	290.7
Base costs (US$/kW)								
Units without CCS	2934							
Units with CCS	4724							

Derate of 25% from CCS

Assume additional derate is also fitted with CCS

For the ten coal using countries selected for study, the composition of the coal fleet to meet projected demand for coal-produced electricity has been calculated in Section 3, together with the concomitant emissions of carbon dioxide. Section 4 sets out the costs of implementing HELE technologies, with and without CCS. The following sections bring together these results by way of summarising the impact of introducing HELE plant to meet demand, the costs involved in doing so and the effect on emissions of carbon dioxide emissions. These are compared with analogous cases where the HELE plant is fitted with CCS. All costs are in US$ – base year 2013. Although firm costs are not yet available for AUSC-based plant, in the light of the very significant carbon dioxide savings possible with this technology, the impact of an AUSC-inclusive fleet fitted with CCS and based on the 25-year retirement scenario is also presented for each country.

Australia

In the Australian base case scenario, no additional capacity is required to meet projected demand for 2020 through 2040. Carbon dioxide emissions range from 162 Mt in 2020 to 144 Mt in 2040.

Under the 50-year plant retirement scenario, new HELE capacity of 1900 MWe is required to meet projected demand at an estimated cost of US$5.6 billion in 2020. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 159 Mt in 2020, a reduction of 3 Mt compared with the base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$11.2 billion which includes an additional 475 MWe to compensate for the CCS-induced derating of the plant, assumed to be 25%. Emissions from the installed HELE capacity would be 12 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 2.3 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 149 Mt in 2020.

Turning to 2040, new HELE capacity of 12500 MWe is required to meet projected demand at an estimated cost of US$36.7 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 117 Mt, a reduction of 27 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$71.9 billion which includes an additional 3125 MWe to compensate for the CCS-induced derating of the plant, assumed to be 25%. Emissions from the HELE plant would be 76 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 14 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 55 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 129 Mt in 2020 and fall to 16 Mt in 2040.

China

In the Chinese base case scenario, no additional HELE capacity is required to meet projected demand for 2020 while 307347 MWe is required to meet projected demand for 2040. Carbon dioxide emissions range from 4256 Mt in 2020 to 6136 Mt in 2040.

Under the 50-year plant retirement scenario, new HELE capacity of 92347 MWe is required to meet demand at an estimated cost of US$270.9 billion in 2020. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 4188 Mt in 2020, a reduction of 68 Mt compared with the base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$545.3 billion which includes an additional 23087 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 561 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 105 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 3732 Mt.

For 2040, new HELE capacity of 307347 MWe is required to meet projected demand at an estimated cost of US$901.8 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 6025 Mt, a reduction of 111 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$2553 billion which includes an additional 108087 MWe to compensate for the CCS-induced derating of the plant. Emissions from the new HELE plant would be 1879 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 281 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 4427 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 4114 Mt in 2020 and fall to 750 Mt in 2040.

Germany

In the German base case scenario, no additional capacity is required to meet projected demand for 2020 through 2040. Carbon dioxide emissions range from 172 Mt in 2020 to 188 Mt in 2040.

Under the 50-year plant retirement scenario, no new HELE capacity is required to meet projected demand in 2020 but phased fleet retirements bringing in new higher efficiency capacity reduce emissions to 167 Mt.

For the 2040 case, new HELE capacity of 9171 MWe is required to meet projected demand at an estimated cost of US$26.9 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 167 Mt, a reduction of 21 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$54.1 billion which includes an additional 2293 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 56 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 10 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 120 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 149 Mt in 2020 and fall to 22 Mt in 2040.

India

For the Indian projections, in the base case scenario no additional HELE capacity is required to meet projected demand for 2020, while 72000 MWe is required to meet projected demand for 2040. Carbon dioxide emissions range from 858 Mt in 2020 to 1444 Mt in 2040.

Under the 50-year plant retirement scenario, no new HELE capacity is required to meet projected demand in 2020.

For 2040, new HELE capacity of 119600 MWe is required to meet projected demand at an estimated cost of US$350.9 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 1348 Mt, a reduction of 96 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$706.2 billion which includes an additional 29900 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 731 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 137 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 754 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 784 Mt in 2020 and fall to 159 Mt in 2040.

Japan

In the Japanese base case scenario no additional HELE capacity is required to meet projected demand for 2020 through to 2040. Carbon dioxide emissions range from 239 Mt in 2020 to 207 Mt in 2040.

Under the 50-year plant retirement scenario, new HELE capacity of 1800 MWe is required to meet demand at an estimated cost of US$5.3 billion in 2020. Carbon dioxide emissions from the coal fleet remain unchanged at 239 Mt. If the new HELE capacity is fitted with CCS, the cost rises to US$10.6 billion which includes an additional 450 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 11 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 2.1 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 230 Mt.

For 2040, new HELE capacity of 4100 MWe is required to meet projected demand at an estimated cost of US$12.0 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 202 Mt, a reduction of 5 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$23.8 billion which includes an additional 1025 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 25 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 4.7 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 182 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 230 Mt in 2020 and fall to 28 Mt in 2040.

Poland

In the Polish base case scenario no additional HELE capacity is required to meet projected demand for 2020 through to 2040. Carbon dioxide emissions range from 159 Mt in 2020 to 172 Mt in 2040.

Under the 50-year plant retirement scenario, no new HELE capacity is required to meet projected demand in 2020.

For 2040, new HELE capacity of 15800 MWe is required to meet projected demand at an estimated cost of US$46.4 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 129 Mt, a reduction of 43 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$93.3 billion which includes an additional 3950 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 97 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 18.2 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 50 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 119 Mt in 2020 and fall to 18 Mt in 2040.

Russia

For the Russian simulation, the base case scenario requires no additional HELE capacity to meet projected demand for 2020, while 3100 MWe is required to meet projected demand for 2040. Carbon dioxide emissions range from 265 Mt in 2020 to 283 Mt in 2040.

Under the 50-year plant retirement scenario, new HELE capacity of 12000 MWe is required to meet demand at an estimated cost of US$35.2 billion in 2020. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 246 Mt in 2020, a reduction of 19 Mt compared with the base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$70.9 billion which includes an additional 3000 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 94 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 17.6 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 170 Mt.

For 2040, new HELE capacity of 26900 MWe is required to meet projected demand at an estimated cost of US$78.9 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 252 Mt, a reduction of 31 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$158.9 billion which includes an additional 6725 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 210 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 39.4 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 81.4 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 182 Mt in 2020 and fall to 28 Mt in 2040.

South Africa

In the South African base case scenario, acute shortages of power necessitate an additional HELE capacity of 5400 MWe is required to meet demand at an estimated cost of US$15.8 billion in 2020. An additional

20700 MWe is required to meet projected demand for 2040. Carbon dioxide emissions range from 308 Mt in 2020 to 402 Mt in 2040.

Under the 50-year plant retirement scenario, new HELE capacity of 8000 MWe is required to meet demand at an estimated cost of US$23.5 billion in 2020. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 303 Mt in 2020, a reduction of 5 Mt compared with the base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$47.2 billion which includes an additional 2000 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 33 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 6.2 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 276 Mt.

For 2040, new HELE capacity of 44500 MWe is required to meet projected demand at an estimated cost of US$130.6 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 356 Mt, a reduction of 46 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$262.8 billion which includes an additional 11125 MWe to compensate for the CCS-induced derating of the plant. Emissions from the new HELE plant would be 272 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 51 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 135 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 254 Mt in 2020 and fall to 49 Mt in 2040.

South Korea

For the South Korean projections, in the base case scenario no additional HELE capacity is required to meet projected demand for 2020, while 3585 MWe is required to meet projected demand for 2040. Carbon dioxide emissions range from 163 Mt in 2020 to 186 Mt in 2040.

Under the 50-year plant retirement scenario, no new HELE capacity is required to meet projected demand in 2020.

For 2040, new HELE capacity of 6785 MWe is required to meet projected demand at an estimated cost of US$19.9 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 356 Mt, a reduction of 46 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$40.1 billion which includes an additional 1696 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 41 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 7.7 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 322 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 158 Mt in 2020 and fall to 23 Mt in 2040.

USA

In the USA base case scenario no additional HELE capacity is required to meet projected demand for 2020 through to 2040. Carbon dioxide emissions range from 1573 Mt in 2020 to 1767 Mt in 2040.

Under the 50-year plant retirement scenario, new HELE capacity of 61328 MWe is required to meet demand at an estimated cost of US$179.9 billion in 2020. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 1441 Mt in 2020, a reduction of 132 Mt compared with the base case scenario. If the new HELE capacity is fitted with CCS, the cost rises to US$362.1 billion which includes an additional 15332 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 375 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 70.3 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 1136 Mt.

For 2040, new HELE capacity of 208000 MWe is required to meet projected demand at an estimated cost of US$610.3 billion. The incorporation of the HELE plant reduces carbon dioxide emissions from the coal fleet to 1445 Mt, a reduction of 322 Mt compared with the 2040 base case scenario.

If the new HELE capacity is fitted with CCS, the cost rises to US$1228.2 billion which includes an additional 52000 MWe to compensate for the CCS-induced derating of the plant. Emissions from the HELE plant would be 1272 Mt unabated. For the HELE plant fitted with CCS (including the additional capacity), emissions would be 238.5 Mt, therefore overall fleet emissions with the HELE/CCS plant installed would be approximately 355 Mt.

For the 25-year retirement scenario, the AUSC/CCS coal fleet's emissions of carbon dioxide are 1268 Mt in 2020 and fall to 208 Mt in 2040.

5 Summarising remarks and conclusions

HELE plant upgrades are considered to be a 'no regret' option for coal plant owners and operators. A current state-of-the-art coal-fired plant operating with a high efficiency ultra-supercritical steam cycle will be more efficient, more reliable, and have a longer life expectancy than its older subcritical counterparts. Most significantly, it would emit almost 20% less carbon dioxide compared to a subcritical unit operating under similar duty. In the near future, the developments in AUSC steam cycles promise to continue this trend, and a plant operating at 48% efficiency would emit up to 28% less carbon dioxide that a subcritical plant, and up to 10% less than a corresponding ultra-supercritical plant.

In this study, by comparing the base case performance of a country's coal fleet without HELE upgrades, other than additional capacity to meet increased demand, with scenarios where older plant is retired and replaced on the basis of a 50-year and 25-year plant life it has been possible to quantify the potential impact of HELE upgrades on emissions of carbon dioxide. The results of the study show trends for the candidate countries, some specific and depending on the profile of their coal fleet and the prospects for growth or decline in coal-sourced electricity, and others more generally applicable. Specifically:

- Countries experiencing a prolonged period of growth necessitating additional capacity and having a relatively new coal fleet have rising emissions of carbon dioxide, but these are offset by the use of AUSC over ultra-supercritical plant for new build (eg China and India).
- Countries experiencing a prolonged period of growth necessitating additional capacity and having a more mature coal fleet have rising emissions of carbon dioxide, but these are offset by the use of AUSC over ultra-supercritical plant (eg South Africa), particularly when older plant is retired and replaced by AUSC units.
- Countries experiencing a prolonged period of growth necessitating additional capacity and having an old and relatively inefficient coal fleet see falling levels of carbon dioxide emissions, even with growth in electricity demand (eg Poland and Russia).
- Countries experiencing relatively low to moderate levels of growth and having an efficient coal fleet do not see significant benefits until 2040 when some older plant is retired (eg South Korea).
- As an existing coal fleet transitions to a HELE composition it becomes smaller in respect of the installed capacity. This has potential benefit for the siting and replacement of plant, particularly in countries where planning regulations are demanding and time consuming.
- The greatest gains are seen when plant life is limited to 25 years (evolving practice in China) rather than 40 years or more (common in OECD countries). Policies and incentives to encourage shorter timescale plant renewal would enhance carbon dioxide savings.
- When CCS readiness is considered, in all cases, the 25-year life scenario represents the best option for CCS deployment as all coal fleets transition to a high HELE content quickly and enjoy maximum carbon dioxide abatement as any remaining lower efficiency capacity is retired. This is particularly evident in the Indian case where the effects of a rapidly increasing demand for electricity and attenuated by a combination of HELE and CCS technologies.

- Economics will govern the decision to replace plant unless policies and incentives drive the selection towards HELE technologies.
- The very significant prospects for shale gas in a number of countries could impact profoundly on the future of coal-fired generation if these are realised in practice.

5.1 Individual country issues

Australia

Carbon dioxide emissions in Australia are projected to decline as a consequence of declining demand for coal-sourced electricity. Having a mature coal fleet, the positive impact of replacing older units with HELE plant is evident for both retirement scenarios with carbon dioxide reductions of 19% and 25% respectively against the 2040 base case (144 cf 117 cf 108 Mt). If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 16 Mt in 2040. Australia is among the most advanced OECD countries with respect to having developed CCS legal and regulatory frameworks and the Australian government is currently seeking views on how high intensity low emissions electricity generation can be progressed. Against this, current practice is for utilities to operate plant for as long as possible and it is reported that there is a general trend away from higher efficiency coal-fired plants. If Australia is to realise the emissions reductions from a HELE upgrade path relevant policies and incentives, perhaps encompassing a detailed analysis of the cost-benefits to utilities of replacing older plant with high efficiency units would be a useful step forward.

China

China is the prime example of a country that is benefitting from an actively pursued HELE upgrade policy. By utilising state-of-the-art ultra-supercritical plant for new and replacement capacity, and through the retirement of old, less efficient units, carbon dioxide emissions are projected to rise less steeply than the increase in demand for coal-sourced electricity, reaching 6136 Mt in 2040. If China continues her policy of adopting the best technology and retiring older units on a roughly 25 year timescale, a largely AUSC-based coal fleet would see projected carbon dioxide emissions fall from 2035 to 5153 Mt in 2040 (a 16% reduction over the base case scenario), despite a continuing upward trend in demand. If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 750 Mt in 2040.

Germany

Clear savings on carbon dioxide emissions are possible for Germany and the recently commissioned new plant will make an important contribution to achieving these. Projected emissions of 188 Mt in 2040 could be cut to 167 Mt and 152 Mt respectively under the 50-year and 25-year scenarios corresponding to reductions of 11 and 19%. If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 22 Mt in 2040. But as with the OECD countries generally, the economic environment makes investment in new coal-fired capacity unattractive and a number of high efficiency units planned have recently been cancelled making future prospects uncertain. By virtue of its significant lignite-power plant capacity Germany is in an interesting position to benefit from the new lignite drying technologies that have been developed where significant efficiency improvements can be realised.

India

India is on track to have the fastest growing coal fleet from 2020 onwards with coal-sourced electricity demand projected to more than double by 2040. The current coal fleet is mostly subcritical, but a large number of supercritical units have been built recently, and more are planned with the majority being supercritical under the 12th Five-Year Plan, and observers suggest that the 13th Five-Year Plan (2017-22) will stipulate that all new coal-fired plants constructed must be at least supercritical. However, the projections in this study show that there are further gains to be achieved from moving to ultra-supercritical plant for replacement even under the modest 50-year plant life scenario, and if AUSC is adopted, carbon dioxide emissions first level out and then decline, despite the increasing demand trend. A largely AUSC coal fleet would generate 1091 Mt in 2040 against a base case of 1444 Mt; a 24% reduction. If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 159 Mt in 2040. Much Indian power generation coal is high in ash and there may be barriers to the adoption of ultra-supercritical technologies, but the significant gains to be had from adopting a HELE pathway warrant a deeper analysis of the Indian situation.

Japan

Japan has a highly efficient coal fleet and therefore minimised emissions of carbon dioxide. Base case emissions of 207 Mt in 2040 and only reduced by 2% under the 50-year scenario to 202 Mt and it is not until the 2040 25-year case that a more substantial reduction to 187 Mt is seen (10%). If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 28 Mt in 2040. Energy policy in Japan is currently under review post Fukushima but high efficiency coal plant is stated to be an important priority focussing on the development of AUSC-based plant and its implementation in the country's energy portfolio.

Poland

Poland is highly dependent on coal and having a relatively mature coal fleet significant emissions savings are possible from HELE upgrades. Base case emissions in 2040 of 172 Mt fall to 129 Mt even under the 50-year case, a reduction of 28% and under the 25-year scenario fall further to 119 Mt, a reduction of 31%. If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 18 Mt in 2040. Recent and planned new Polish capacity is supercritical whereas the greatest reductions would be realised through ultra-supercritical plant. There are some doubts on how Poland will source her future coal supplies and this will impact directly on coal's place in the energy mix in the medium to long term. Also, recent discoveries of shale gas in Poland may potentially reshape the prospects for traditional fuels in the country's energy mix. The potential reductions that could be realised under a Polish HELE pathway warrant further study to better quantify the benefits in the context of the country's developing energy market.

Russia

The Russian coal fleet is relatively mature and of low efficiency and offers the highest carbon dioxide savings, in percentage terms under a HELE upgrade path. Base case emissions of 283 Mt in 2040 fall to 252 Mt under the 50-year scenario (an 11% reduction), and to 190 Mt under the 25-year scenario a 33% reduction. If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 28 Mt in 2040. Although the Russian situation is difficult to research the potential reductions that could be realised warrant further study to better quantify the benefits.

South Africa

South Africa is currently commissioning new capacity to meet a shortfall in electricity supply and to progress the country's ambitious economic growth aspirations as evidenced by the projected increase in electricity demand. With a mainly subcritical coal fleet there is a significant potential for emissions reduction through a HELE upgrade pathway. A base case level of 402 Mt falls to 356 Mt and then to 328 Mt under the 50-year and 25-year scenarios, respectively (reductions of 11% and 18% against a rising demand curve). If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 49 Mt in 2040. New capacity is based on supercritical technology and higher duty steam cycles would give greater savings if appropriate to the South African situation. The country's energy policy is currently under review to determine what additional capacity might be required under different growth projections. The options under consideration include the relative merits of life-extending existing plant verses replacement with new capacity. A deeper analysis of the South African situation would be valuable in further clarifying the potential benefits from HELE upgrades.

South Korea

South Korea is similar situation to Japan in that the coal fleet is already highly efficient, limiting potential savings. Base case emissions for 2040 are 186 Mt, falling to 182 Mt and 159 Mt respectively under the 50-year and 25-year scenarios corresponding to reductions of 2% and 15%. If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 23 Mt in 2040. South Korea has active policy of HELE capacity for new coal-power builds, but the country's energy policy puts the emphasis firmly on the development and exploitation of renewable power sources.

USA

The USA is projected to remain the second largest emitter of carbon dioxide, after China, in 2040 with a total of 1767 Mt in 2040. The analysis presented in this study shows that there are large potential savings to be had from HELE upgrades. Specifically, projected emissions of 1767 Mt in 2040 under the base case could be cut to 1445 Mt under the 50-year scenario and 1392 Mt in 2040 corresponding to reductions of 18% and 21% respectively. If the most effective carbon dioxide abatement pathway is followed (25-year plant retirement, AUSC upgrades after 2025, CCS installation) emissions could fall to 208 Mt in 2040. Currently coal is losing market share against an increasing supply of low cost shale gas which has the additional benefit of lower emissions of carbon dioxide. Consequently, this makes coal's future in the US difficult to predict and again it is likely that policy and incentive measures would be required to encourage HELE uptake.

6 Suggested next steps

The prospects for a country's coal fleet are governed by complex interacting factors including but not limited to; regional policy, the economic landscape, evolving legislation and competing energy supplies. While the scope of this study using a methodology developed with, and based on, published validated data is valuable in setting out the potential for HELE technologies in carbon dioxide abatement in different countries, it is recognised that this needs to be followed-up by deeper analysis to reflect these factors in greater detail for each country. The present study is therefore considered to be a gateway document which could lead to a set of individual country studies similar to the IEA CCC 'Clean coal prospects in…' series where country-specific factors are considered in detail, and the views of major stakeholders within each country incorporated wherever possible, to give a more comprehensive view on regional HELE implementation pathways. Based on the analysis in this study and summarised in the concluding remarks on individual country issues the initial priority areas for further study are considered to be:

- India;
- South Africa;
- Poland;
- Russia.

Although the majority of coal users have been included in this study, it is recognised that a significant minority coal using countries need to be researched to complete the world view. Of these countries, the rapidly developing 'Asian Tiger' coal-users form an important and relevant set for study. It is therefore recommended that a further overview study on HELE prospects is undertaken for these states.

Finally, it is recognised that plant improvements both minor and major and modifications to day-to-day operating practice can contribute to significant efficiency gains at relatively low cost. It is there recommended that an updated review of the current best practices in OECD countries and in China where great progress has been made in this area to identify and quantify topics and techniques that could lead to knowledge transfer opportunities.

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