An overview of HELE technology deployment in the coal power plant fleets of China, EU, Japan and USA

Dr Malgorzata Wiatros-Motyka

CCC/273

December 2016

An overview of HELE technology deployment in the coal power plant fleets of China, EU, Japan and USA

Author: Dr Malgorzata Wiatros-Motyka

IEACCC Ref: CCC/273

ISBN: 978–92–9029–596-9

Published Date: December 2016

IEA Clean Coal Centre
14 Northfields
London SW18 1DD
United Kingdom

Telephone: +44(0)20 8877 6280

www.iea-coal.org

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, China, the European Commission, Germany, India, Italy, Japan, Poland, Russia, South Africa, Thailand, the UAE, 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

The coal-fired power fleets in China, Japan, the EU and the USA are compared. Data from existing plants, of 300 MW or larger capacity, as well as those under construction and planned are reviewed. Plants are compared in terms of deployed technology (subcritical, supercritical and ultrasupercritical) as well as their age and installed pollution control equipment. Examples of some of the most efficient plants in each region are described, including Guodian Taizhou II unit 3 in China, Maasvlakte Power Plant 3 in the Netherlands, Isogo unit 2 in Japan and the John Turk Jr coal-fired plant in Arkansas, USA. The coal fleet in Japan is the most efficient in the world, followed by China, the EU and then the USA. All the regions studied have active research programmes to increase the efficiency of coal-fired plant and to reduce emissions. This survey also investigates the attitudes of the governments towards high efficiency and clean coal power technologies as well as drivers and barriers to their use.

Acronyms and abbreviations

AUSC	advanced ultrasupercritical
BAT	best available technologies
BREF	BAT reference documents (EU)
CAA	Clean Air Act
CCS	carbon capture and storage
CCT	clean coal technologies
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation and storage
CHP	combined heat and power
CPP	Clean Power Plan
CTF	Component Test Facility
CTL	coal-to-liquids
CBTL	coal-and-biomass-to-liquids
DOE	Department of Energy (USA)
EIA	Energy Information Administration (USA)
EOR	enhanced oil recovery
EPA	Environmental Protection Agency (USA)
ESP	electrostatic precipitator
ETS	Emissions Trading System
EU	European Union
FF	fabric filter (bag house)
FGD	flue gas desulphurisation
FYP	Five-Year Plan
gce	grammes of coal equivalent
HELE	high efficiency, low emissions (coal-fired plant)
HHV	higher heating value
IEA	International Energy Agency
IEA CCC	IEA Clean Coal Centre
IED	Industrial Emissions Directive (EU)
IGCC	integrated gasification combined cycle
IGFC	integrated gasification fuel cell combined cycle
LHV	lower heating value
LNB	low-NOx burner
LNG	liquefied natural gas
NETL	National Energy Technology Laboratory (USA)
NSPS	New Source Performance Standards
MATS	Mercury and Air Toxics Standards
Mtoe	million tonnes of oil equivalent
OECD	Organisation for Economic Co-operation and Development
PM	particulate matter
RFCS	Research Fund for Coal and Steel
R&D	research and development
SCR	selective catalytic reduction
SNCR	selective non-catalytic reduction
SC	supercritical
USC	ultrasupercritical

Contents

List of Figures

List of Tables

1 Introduction

Coal plays a significant role in the world's energy mix. However, the average efficiency of coal-fired power generation units in the major coal-using countries varies enormously, from under 30% to over 47% (LHV, net). This is due to many factors, including the age of operating plants, the steam cycle conditions, local climatic conditions, coal quality, operating and maintenance practices, and receptiveness to the uptake of advanced technologies (IEA, 2012, 2016a). Of these factors, the steam cycle conditions have a major impact on plant performance. Differences in average efficiencies translate to differences in levels of CO_2 and other pollutants emitted per kWh of electricity. There are also vast variations in the deployment of control technologies for major pollutants: nitrogen oxides (NOx), sulphur oxides (SOx) and particulate matter (PM) and their consequent emission levels. All of these pollutants cause environmental and health problems. Hence, nations are tightening their emission standards as well as pledging to reduce their CO_2 emissions following the United Nations climate change conference (COP21) in Paris (December 2015). Consequently, coal-fired power plant fleets must continue to become more efficient and less carbon intensive.

Deployment of high efficiency, low emission (HELE) technologies increases the efficiency of coal-fired power plants and reduces their CO_2 intensity (*see* Table 1). In contrast to subcritical plants, HELE plants, namely supercritical (SC) and ultrasupercritical (USC), operate at higher steam cycle conditions, hence they use less coal per unit of electricity produced and emit fewer pollutants. Definitions of supercritical and ultrasupercritical conditions vary. However, the following temperature and steam ranges are used frequently: <22.1 MPa and up to 560°C for subcritical steam conditions; 22.1–25 MPa/540–580°C for supercritical; and >25 MPa/>580°C, for ultrasupercritical units (Nalbandian, 2008). The recent USC plants operate with temperatures of 600°C and above (IEA, 2011).

Table 1 CO_2 intensity factors, average (LHV, net) efficiencies and fuel consumption values as a function of plant steam cycle condition (modified from IEA, 2012; VGB, 2011; Henderson, 2016)

	CO_2 intensity factor	Efficiency (LHV, net)
A-USC (700°C)† IGCC (1500°C)‡	670–740 g CO_2/kWh	45–50%
Ultrasupercritical	740–800 g CO_2/kWh	up to 45%
Supercritical	800–880 g CO_2/kWh	up to 42%
Subcritical	≥880 g CO_2/kWh	up to 38%

† steam temperature; ‡ turbine inlet temperature

Note: the CO_2 intensity factor is the amount of carbon dioxide emitted per unit of electricity generated from a plant. For example, a CO_2 intensity factor of 800 g CO_2/kWh means that the coal-fired unit emits 800 g of CO_2 for each kWh of electricity generated.

Despite supercritical and ultrasupercritical technologies being available for a few decades (USC since the 1990s), in 2011 only approximately 50% of new coal-fired power plants fell into this category. Around 75% of operating units used subcritical non-HELE technology, and more than half of the capacity was over

25-years old and consisted of units smaller than 300 MW capacity (IEA, 2012). Obviously, all countries and regions have different histories, circumstances, economies and needs in terms of energy generation and consumption as well as different drivers and barriers for the implementation of technologies. Therefore, there are vast differences in countries' coal-fired fleets.

China, Japan, the EU and the USA have the world's strictest emission limits for coal-fired power plants (IEA, 2016b). They are frequently used as reference values in national and international debates on the redefinition of future threshold values for coal-fired power stations. Hence, data from these regions are of particular interest, especially now as countries develop strategies to meet their COP21 climate targets. This report analyses the current coal-fired power fleets in the selected areas, in terms of deployed technology and pollution control systems, and shows the general trends. Only plants of capacity of 300 MW or larger were analysed. This is because the report focuses on the best available HELE technologies and they can only be applied to plants larger than 300 MW (IEA, 2012). The focus on HELE plant is also due to the fact that they can be fully integrated with an appropriate new or retrofit CO_2 capture technology more economically than subcritical plants (Nalbandian, 2008; IEA, 2012). Furthermore, as pulverised coal combustion (PC) is the most widely used technology in coal-fired power plants globally, only pulverised coal-fired units were taken into account during the profiling of each fleet. The study also looks also at plants under construction and those planned in the near future (up to approximately five years ahead) where possible, although many of these planned power plants may not be realised. This is due to uncertainties regarding countries' future policies. For example, China's next Five-Year Plan (FYP) will be decided over the next year or so, whereas in the USA, the future energy mix will be shaped by the implementation or not of the Clean Power Plan (CPP) as well as lower prices for renewables and natural gas. Additionally, many currently operating plants may be retired, replaced or forced to operate only as backup for intermittent sources such as solar and wind. In cases where smaller units retire, the larger ones may need to operate at higher levels (EIA, 2016b). Also, some coal-fired power plants may be converted to biomass or biomass cofiring.

Investment decisions and key technology choices for power plants are extremely important as they create technology 'lock in' which impacts efficiency and emissions levels for decades to come (IEA, 2012). Hence, this survey also investigates the attitudes of the governments towards high efficiency and clean coal power technologies as well as barriers and drivers to their use.

2 Background and methodology

Chapter 2 explains how the individual coal-fired power plant fleets were profiled and some of the uncertainties and factors affecting reported values are highlighted. Similarly, there is no standard methodology to measure and report power plant performance in terms of its efficiency and CO_2 emissions and many different bases and assumptions are used around the world (IEA, 2010). Therefore, aspects of power plant design and operations that influence efficiency performance and related CO_2 emissions are also briefly explored.

2.1 Profiling individual coal fleets

A profile of each country's or region's fleet was prepared based on data extracted from Platts World Electric Power Plants Database, as of March 2016. However, only units of 300 MW or greater capacity were considered for reasons outlined in Chapter 1.

Plants were categorised into groups by date of commissioning and steam cycle conditions (subcritical, supercritical and ultrasupercritical) and whether operating, under construction or planned. As explained in Chapter 1, there are various definitions of supercritical and ultrasupercritical plants. Platts database does not specify the exact steam cycle conditions used for categorising plants as subcritical, supercritical and ultrasupercritical, and information on main and reheat steam temperatures is not available for all power plants. However, plants for which steam conditions are provided are categorised by the most commonly used values, as reported by Nalbandian (2008): <22.1 MPa and up to 560°C for subcritical steam conditions; 22.1–25 MPa/540–580°C supercritical; and >25 MPa/>580 °C for ultrasupercritical. Consequently, the assumption was made that the Platts classification of plants was correct even for those plants for which steam cycle conditions were not provided.

Platts database is widely used and updated quarterly in December, March, June, and September. However due to rapid changes in the energy sector, especially in China, there are some uncertainties. For example, some power plants categorised as under construction were found to be already in operation. Hence data has been cross-checked with various sources where possible, including power plant companies' webpages and personal communications, and updated. For the EU plants, the data from Platts were cross-checked with the VGB power plants database. Japan's coal fleet was cross-checked with the JCOAL database. Data on plants under construction based on Platts database was also cross-checked with other information. Similarly, information on planned coal-fired plants was taken from Platts database. However as pointed out by Platts – their database 'is not a forecasting tool'. Hence data on planned plants should be treated with caution as many of those planned may not be built due to changing policies and circumstances.

The reported capacity of all plants, operating, under construction and planned, represent gross capacity values.

Data on pollution control systems for NOx, SO_2 and PM trends is provided based on information from Platts database. However, there is a lack of information for some power plants, which does not mean that there is no pollution control equipment. It means that there is no information available for use in the database and according to Platts, it is highly unlikely that these plants do not have such technologies (Platts, 2016). For the USA, the information on pollution control equipment was cross-checked with the US EPA Power Sector Modeling Platform v.5.15 database (https://www.epa.gov/airmarkets/power-sector-modeling-platform-v515).

2.2 Reporting plant efficiencies and CO_2 emissions

This work does not calculate efficiency and CO_2 emissions of the analysed fleets but quotes estimated average values from various sources, including the power plant owners and various national and international statistics.

2.2.1 Factors affecting measurement and reporting of efficiencies and CO_2 emissions

In spite of concerted efforts over many years, there is no common methodology to measure and report power plant performance in terms of its efficiency and so reported values should be treated with caution (IEA, 2010). As CO_2 emissions are closely related to power plant efficiency, both areas are fraught with difficulty (CIAB, 2010; Sloss, 2011; ECOFYS, 2014, Barnes, 2014). This is due to many factors. The operating efficiency of the plant will probably vary from its designed efficiency, as plants often operate under off-design conditions, especially at part–load operation. Operating at part-load always lowers the efficiency. Similarly, a number of perturbations such as frequent shut-down and start-up of the plant, will reduce efficiency. Disruptions from steady state operation can lead to a physical deterioration of the plant which also affects its efficiency. The overall efficiency of a power plant will diminish over its life time as various components such as the steam turbine deteriorate. This can be mitigated to some extent by operating and maintenance best practice. Furthermore, there are some efficiency losses due to the transfer of heat energy to the working fluid of the power cycle.

Other constraints which impact coal-fired power plant efficiency include:

- poorly operating auxiliary equipment;
- high coal moisture and ash content which impact the latent and sensible heat losses, heat transfer and auxiliary plant load;
- fuel sulphur content as it sets design limits on the boiler flue gas discharge temperature;
- local climatic conditions (ambient air temperature and humidity) affect the capacity of cooling towers and natural water bodies to transfer waste heat from steam condensers to the atmosphere;
- installed pollution control equipment as it increases on-site power demand;
- use of low-NOx combustion systems as these may increase the unburnt carbon; and
- the type of cooling-water system used (such as closed-circuit, once-through or coastal cooling water system) as it determines the cooling water temperature.

In most cases there is little that can be done to mitigate these effects as they are not a result of inefficient design or operation but a function of 'real plant design constructions' (IEA, 2010).

The operating efficiencies of power plants are not generally made available by their owners and may be considered as sensitive or confidential information (Henderson and Baruya, 2012; Barnes, 2014). Even when data are available, the reported efficiency of two identical plants, or even the same plant tested twice may differ. Further, the basis for reporting is often not clear. For example, values are quoted without specifying if they are based on higher heating value (HHV) or lower heating value (LHV), 'gross' or 'net' output. For most power station coals, efficiencies based on HHV are generally 2–3% points lower than those based on LHV, because LHV does not account for the latent heat of water in the products of combustion (Barnes, 2014). Where a plant is firing high moisture coals, such as many lignites, the efficiency calculated on an HHV basis is much lower than the LHV-based value, possibly by five or six percentage points. Values referred to as 'gross' and 'net' energy outputs, relate to the use of a proportion of the output energy by the process itself. Hence the output referred as 'gross output' is power plant energy before any deduction, whereas 'net output' is the value after the deduction for own use.

2.3 Drivers and barriers for implementation of advanced clean coal technologies

Investment decisions and key technology choices for power plants are extremely important as they 'lock in' technology, which impacts efficiency and emissions levels for decades to come (IEA, 2012). Therefore, drivers and barriers for the implementation of advanced clean coal technologies in the investigated countries and regions have been evaluated based on their current energy-related policies, funding mechanisms, various projections and analyses from sources such as the International Energy Agency (IEA), the US Energy Information Administration (EIA), and the European Commission (EC), as well as from in-house expertise. The following chapters consider these factors in detail for each area studied.

3 China

Currently, China has a total installed capacity of around 900 GW of coal-fired plants. This represents almost half of global coal-fired capacity and makes the Chinese fleet the world's largest. A further 150–200 GW is reported to be under construction (IEA, 2016a). In recent years China has shown a strong commitment to addressing environmental issues related to air quality, natural resources management and climate change. While expanding its coal-fired fleet, China has taken various actions to ensure that the new fleet has a high efficiency and a reduced environmental impact. Consequently, China's fleet has reached the point where its average operational efficiency of 38.6% LHV exceeds the average across coal-fired plants in the IEA member countries (IEA, 2016a). Furthermore, its environmental standards for new power plants are among the most stringent in the world, so each power plant is equipped with dust and sulphur control equipment, and 95% of plants have nitrogen oxide control, the rest have circulating fluidised bed (CFB) systems (Li and Yu, 2016). Much of the material in this chapter is found in more detail in another report from the IEA Clean Coal Centre by Zhu (2016).

3.1 Profile of existing coal fleet

As China's economy has grown, so has its coal-fired fleet, accompanied by the implementation of more advanced coal technologies (supercritical and ultrasupercritical). In 2014 coal-fired plants contributed just over 67% of total installed capacity and generated around 75% of electricity (Li and Sun, 2015; Li and Yu, 2016). As reported by Li and Yu (2016), the average net coal consumption rate of the Chinese fleet has decreased steadily from 380 g/kWh in 2003 to 318 g/kWh in 2014 (*see* Figure 1). This trend is expected to continue and in 2020 average net coal consumption rate is anticipated to be below 310g/kWh. The net consumption rates are based on gce (grammes of coal equivalent) which uses as a basis a standard coal equivalent of 29.31 MJ/kg (Henderson, 2016). The change in net consumption rate obviously goes in tandem with the increase in the average net plant efficiency, which rose from just over 32% in 2013 to approximately 38.6% (LHV, net) in 2014 (IEA, 2016a). At the same time, China has closed many units that were smaller than 300 MW and increased the number of units that are 600 MW and larger (*see* Figure 3). By the end of 2014, there were 561 units in this size range, of which 71 were 1000 MW ultrasupercritical plants with a combined capacity of 375.77 GW (Li and Yu, 2016). These changes are the results of government policies on pollution control, energy efficiency and other measures (*see* Section 3.3). For more detail *see* Zhu (2016).

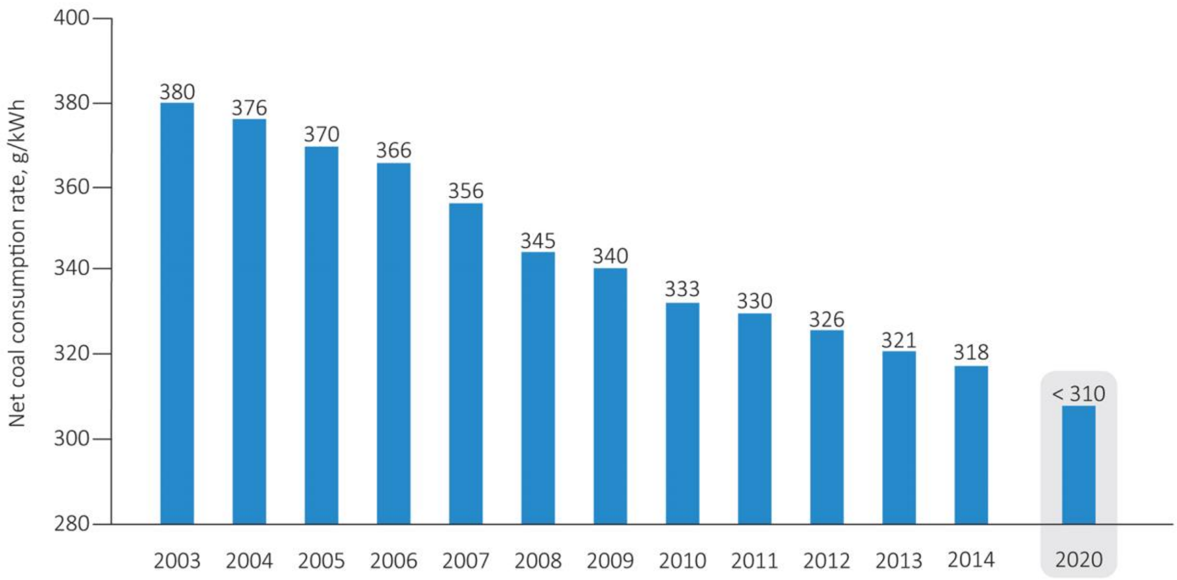

Figure 1 The average coal consumption rate of plants in China (Li and Yu, 2016)

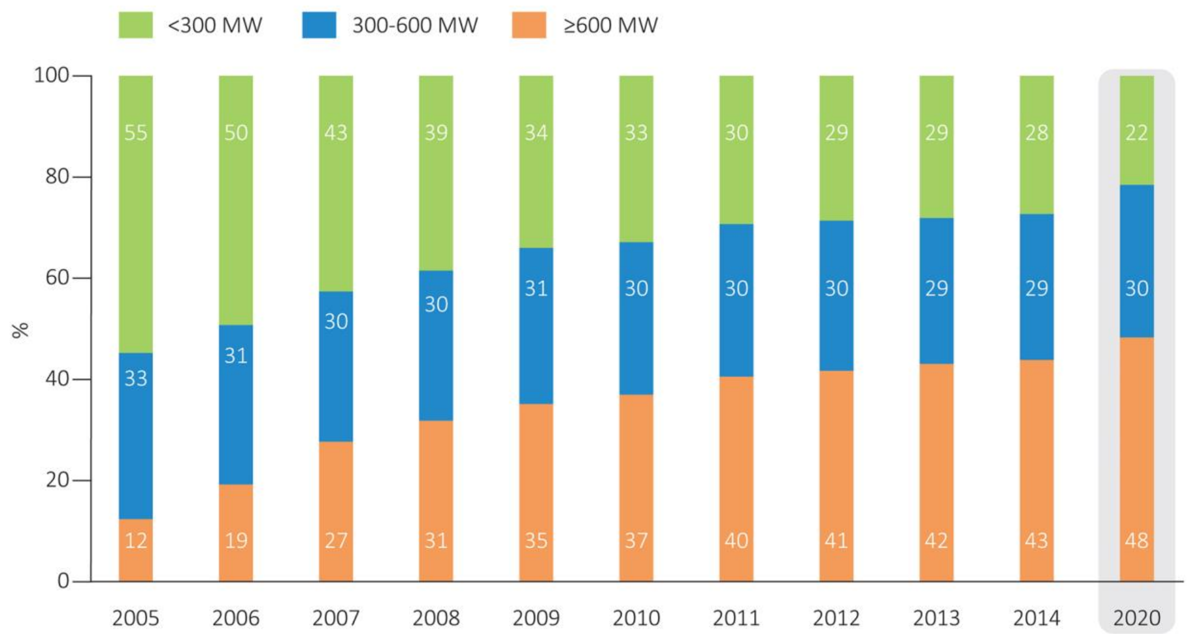

Figure 2 Structure of China's coal-fired fleet, by unit size (Li and Yu, 2016)

Data analysed for this report show that currently (March 2016) there are over 1650 units of 300 MW capacity or greater. They have a combined capacity of over 746 GW, which represents around 83% of China's total coal-fired capacity. This is an 11% increase from data reported by Li and Yu for the year 2014 (*see* Figure 2). As shown below in Figure 3 and Figure 4, of these, 51% are subcritical, 29% supercritical and 20% ultrasupercritical units. Around 87% of them have been built since 2000. Since 2010, more plants have been built as ultrasupercritical, than either supercritical or subcritical (*see* Figure 4).

Tables 4–6 show details of each subcategory (subcritical, supercritical and ultrasupercritical) in the current fleet by age.

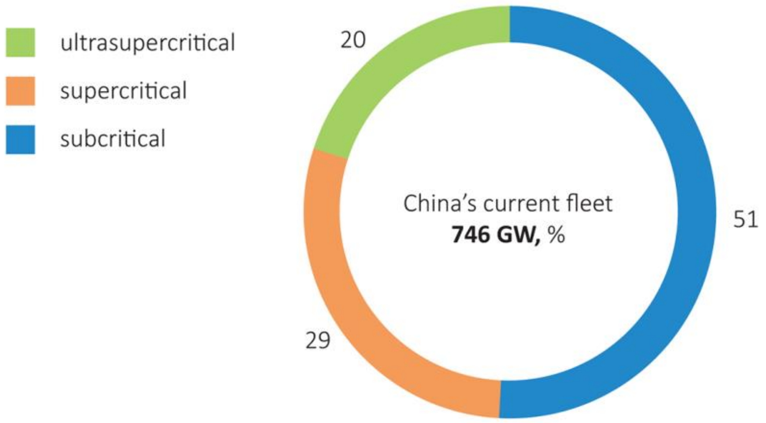

Figure 3 Operating coal-fired fleet in China

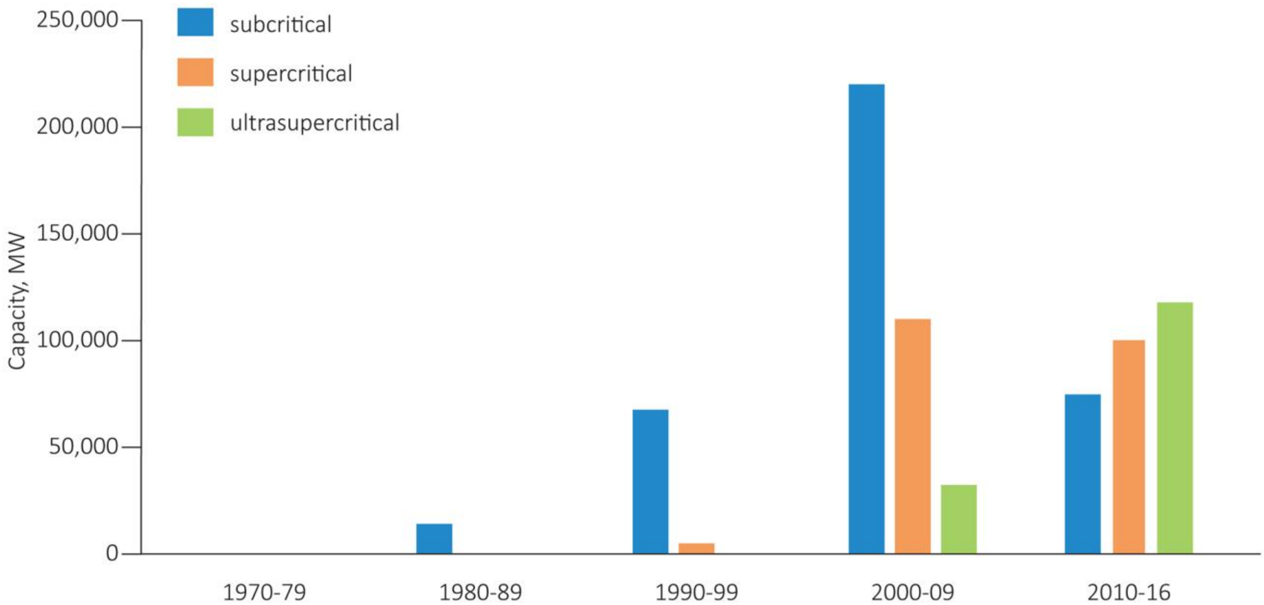

Figure 4 China's coal fleet, by age

Table 2 Subcritical coal-fired fleet in China

Year of commissioning	Unit number	Size range (MW)	Total capacity of the group (MW)	Subcritical capacity (%)	Perentage of total capacity (%)
1970-79	3	300–310	923	0.2	0.1
1980-89	39	300–677.5	14471.5	3.8	1.9
1990-99	201	300–677.5	67838.5	17.7	9.0
2000-09	597	300–700	221740	57.7	29.5
2010-16	219	300–700	75020	19.5	10.0
Total	1059		379993	98.9	50.6

Table 3 Supercritical coal-fired fleet in China					
Year of commissioning	**Unit number**	**Size range (MW)**	**Capacity of the group (MW)**	**Supercritical capacity (%)**	**Percentage of total capacity (%)**
1990-99	11	320–600	5080	2.4	0.7
2000-09	180	350–980	110250	51.1	14.7
2010-16	202	300–1000	100410	46.5	13.4
Total	393		215740	100	28.8

Table 4 Ultrasupercritical coal-fired fleet in China					
Year of commissioning	**Unit number**	**Size range (MW)**	**Total capacity of the group (MW)**	**Ultrasupercritical capacity (%)**	**Percentage of total capacity (%)**
2000-09	40	600–1050	32390.2	21.5	4.3
2010-16	142	600–1100	118306	78.5	15.8
Total	182		150696.2	100	20.1

As reported by the China Electricity Council (Wang, 2016) and EPPEI (Li and Yu, 2016), China's air pollution control policies and measures have been successful in terms of particulate matter (PM) control, and recently electrostatic precipitators (ESP) have been replaced with bag filters or EP bag filters (electrostatic bag filters). In 2015, the proportion of plants using ESP decreased to 69%, from 95% in 2010, while the use of bag filters or EP bag filters increased from 5% to 31% in the same time. The average efficiency of PM removal was over 99.9% in 2015. The average emission rate of PM dropped from 10.5 g/kWh in 1985 to below 0.09 g/kWh in 2015 (Wang, 2016). China is committed to further reductions in PM emissions and is developing more advanced control technologies such as low temperature ESP and wet ESP (Wang, 2016; Zhang, 2016).

In 2015, 92.8% of the coal-fired capacity had desulphurisation technology in place. The remainder of the plants are circulating fluidised bed boilers (CFB), which effectively means that all coal-fired units have sulphur control. Consequently, the average emission rate of SO_2 from coal-fired power plant generation decreased from 6.4 g/kWh in 2005 to below 0.49 g/kWh (Wang, 2016). The dominant form of desulphurisation technology is FGD and its variations such as wet, dry FGD, or limestone based, which account for approximately 65% of desulphurisation installations. However, there is a lack of information on the specific technology type used for about a fifth of the coal-fired power plants in Platts database (as of March 2016).

The number of NOx control installations has increased rapidly in the last five years. In 2015, 95% of coal-fired plants had NOx control equipment in place, which is more than a 70% increase since 2011. Plants without specific NOx control installations have CFB boilers (Wang, 2016). In addition, most plants use low-NOx burners. This effectively means that all coal-fired plants have some form of NOx control in place.

Platts database shows that the dominant form of NOx control is selective catalytic reduction (SCR). Other options include: low-NOx burners, staged combustion, and boosted overfire air (BOFA), although these are installed to a much lesser extent. However, there is a lack of information on the specific technology type used for over one-third of the plants.

Mercury (Hg) can be removed from coal-fired power plants in the pollution control devices designed to remove other air pollutants including SCR, FGD and PM control systems. This is termed removal as a co-benefit. More than 90% of the mercury can be removed depending on factors such as the control system used and the type of coal. As China has high rates of installation of PM, NOx and SOx pollution control, the required mercury removal rate (30 µm/m^3) is most likely to be met as a co-benefit.

China has some of the cleanest and most efficient coal-fired plants in the world. These include two 1000 MW capacity ultra-low emission USC units – Unit 3 and 4 at Anqing Power Plant (*see* Figure 5). Both boilers benefit from a number of innovative solutions which lead to an overall plant net efficiency of over 45% (LHV) as well as coal consumption rates of 272.5 g/kWh (unit 3) and 273.9 g/kWh (unit 4), which are lower than the national average (*see* Figure 1 on page 15) (Baruya, 2016; Zhu, 2016). As noted by Zhu (2016), such low rates of coal consumption saves around 166,650 t/y of coal which is equivalent to about 416,700 t CO_2/y, and corresponds to a 5% decrease in CO_2 emission compared to the average 1000 MW plant in China. The units have main and reheat steam temperatures of 600°C and 620°C, respectively, which are the highest in China in units of this size (Zhu, 2016). Additionally, their steam turbine back pressure (4.89 kPa) is lower than that for a standard unit (5.1 kPa), which reduces coal consumption by about 0.21 g/kWh. Additional innovations which increase efficiency and reduce heat consumption include: nine steam extraction stages (typically there are eight); flue gas waste heat recovery; and improved cooling tower design. Details can be found in another IEA CCC report by Zhu (2016). Units have ultra-low emissions of 3, 5 and 20 mg/m^3 for PM, SO_2 and NOx, respectively, which are achieved by advanced flue gas treatment technologies. A low-NOx combustion system and SCR using urea as a reducing agent are used for NOx control. For SO_2 and partial PM control, spin exchange coupling FGD (SPC FGD), developed by the Guodian Qingxin Company, is used. The system achieves 97.8–99.7% SO_2 removal rates and consumes less power and water than other FGD systems (Zhu, 2016). PM is controlled in three stages. The first stage takes place in a low-temperature economiser and high-frequency ESP, which removes approximately 99.86–99.9% of dust. The second one is in the SPC FGD, where approximately 60% of the remaining particulates are removed simultaneously with SO_2. The final stage is carried out in the rotary tube bundle PM demister, which has a removal efficiency of over 70%. Additionally, 100% of fly and bottom ash as well as desulphurisation by-products are utilised and there is no wastewater discharge (Zhu, 2016).

Figure 5 Anqing power plant

Chinese innovation is also found at the 1000 MW double reheat USC Guodian Taizhou II unit 3 and unit 4 (*see* Figure 6). Unit 3 started commercial operation in September 2015 and unit 4 in January 2016. Both units are domestically designed, manufactured and built. According to Zhu (2016), unit 3 has reached a plant efficiency of 47.82% (net, LHV), the highest in China and in the world for a double reheat coal-fired power plant. Its emissions are: PM – 2.3 mg/m^3, SO_2 – 15 mg/m^3 and NOx – 31 mg/m^3. Unit 3 coal consumption is 256.8 g/kWh, which is 6 g/kWh lower than the previous world's best value and around 14 g/kWh lower than the coal consumption of an average single-reheat USC 1000 MW unit. The CO_2 emissions of Taizhou II units are 5% lower than those of conventional (single reheat) 1000 MW class USC coal power generating units. Consequently, both units can save a total of 151,800 t/y of coal (Zhu, 2016).

Figure 6 View of turbine in one of the units in Guodian Taizhou II

3.2 Coal fleet under construction and planned

According to Platts database, there are 184 units of total capacity of 112,180 MW under construction (*see* Table 5). The majority of these are ultrasupercritical (67%) and supercritical units (26%).

Table 5 Coal-fired plants under construction in China (based on Platts data as of March 2016, only units of ≥300 MW)

Year of commissioning	Number of units	Capacity (MW)	Size range (MW)	Plants under construction (%)
Subcritical	21	7 410	300–600	7
Supercritical	68	28 640	350–660	26
Ultrasupercritical	93	75 530	600–1100	67
Total	184	112 180		100

As for planned capacity, Platt's database lists 445 units with a total capacity of 294,588 MW. Of these, 135 units are classified as ultrasupercritical, 145 as supercritical, 85 as subcritical and there is no information on 80 of them. However, it is highly unlikely that all of these plants will be constructed. Since 2006 design standards in China have required new pulverised coal combustion plants to be SC or USC and to have a minimum capacity of 600 MW. Since 2015 the unit capacity of most new coal power projects has been 1000 MW USC (*see* Section 3.4.1). This means that the smaller units are extremely unlikely to be constructed. Further, the emergence of overcapacity means that not all the planned plant will be built (*see* Section 3.4).

3.3 Research and development

China's commitment to improving the efficiency of its coal-fired fleet is evident in the investment in R&D of HELE technologies such as advanced ultrasupercritical (AUSC) plant, for which a component test facility was commissioned at the end of 2015. There is also considerable work under way on double reheat cycles, which have been applied to two large plants (Huaneng Anyuan – 2 x 600 MW and Goudian Thaizhou – 2 x 1000 MW – described above in Section 3.1). Additionally, there is a new idea to split the turbines onto two levels to reduce steam pipe length and improve efficiency (Lockwood, 2016). China is also researching gasification technology and has an IGCC demonstration project (GreenGen Project) in Huaneng, Tianjin. The 250 MW IGCC demonstration unit started operation in 2013 and by 10 September 2014 had operated for a total of 3200 h. The longest period of continuous operation was 45 days. During operation, the average coal consumption was 385 g/kWh. Emission levels were: SO_2 – 0.9 mg/m^3, NOx – 50 mg/m^3 and PM – 0.6 mg/m^3 (Zhu, 2016). This project is currently in its third phase which encompasses a 400 MW plant with polygeneration and CCS (Lockwood, 2016). Research into CCS is ongoing and there have been three pilot- or demonstration-scale projects so far. R&D work is also under way on fuel cells based on coal (Li and Yu, 2016). More information on R&D in China can be found in an IEA CCC report by Zhu (2016).

3.4 Drivers and barriers for implementation of advanced clean coal technologies

While expanding its coal-fired fleet, China has taken significant steps to reduce its overall pollution. A number of policies and action plans related to local pollution, greenhouse gases, energy mix and natural resources have been developed and implemented. Many of the consequent laws, standards, regulation plans, targets and others, have an impact on existing and new coal-fired power plants. The main targets and other considerations are summarised in Section 3.3.1, while their detailed descriptions can be found in Zhu (2016). The main drivers for the implementation of advanced clean coal technologies in China are strong policies and tight environmental and performance standards to be implemented rapidly. These drivers are combined with available finance and subsidies in the form of feed-in tariffs for energy generated from ultra-low emission power plants are. However, the motivating factors are:

- a strong desire to reduce the health and social costs of local air pollution;
- a commitment to reduce greenhouse gas emissions;
- concern about the environment and natural resources; and
- a desire to have a diverse electricity mix for energy security purposes.

Barriers to the construction of coal-fired power plants include limited water resources and competition for them from other industries and agriculture. Potential overcapacity in some regions and actual overcapacity in others, and the rapid development of renewables which can reduce the profitability of coal-fired power plants, are other examples of barriers (Zhu, 2016; Power Engineering International, 2016). The next section outlines the drivers and barriers in the Chinese policy framework.

3.4.1 Overview of policy and regulatory framework

For over three decades, China's economy has grown rapidly. This was due to a strategy of high investment, strong export orientation and energy-intensive manufacturing. Hundreds of millions of people were lifted out of poverty. However, such rapid growth also highlighted problems of inequality and environmental damage (Green and Stern, 2015). Recognising the challenges, China has developed a new economic model – 'new normal'. It focuses on structural changes that can attain strong but lower economic growth (around 7% per year over the next five years) with much better social distribution and significantly reduced impact on the natural environment. The 'new normal' emphasises: shifting the balance of growth away from heavy-industrial investment and toward domestic consumption; reducing inequalities, especially urban–rural and regional inequalities; environmental sustainability, emphasising reductions in air pollution and preventing environmental damage, as well as reducing GHG emissions. This new model translates into a number of action plans, policies and instruments which relate to the coal-fired sector.

For example, the 2014-2020 National Plan on Climate Change aims for 40–45 % reduction of CO_2 emissions by 2020, from 2005 levels. Whereas China's Intended Nationally Determined Contribution (INDC), following COP21 in Paris, 2015, extends existing national targets for 2020 and sets out the targets for 2030 as follows:

- CO_2 emissions to peak by 2030, or earlier if possible;
- CO_2 emissions per unit of GDP to reduce by 60–65% from 2005 levels;
- the share of energy from non-fossil sources to increase to 15% in 2020 and to 20% in 2030;
- from 2014, new coal power plants should consume no more than 300 gce/kWh (equivalent of 40.9% net, LHV efficiency), and attain an operational average for all power plants of 310 gce/kWh by 2020; and
- a total primary energy supply cap of 4.8 billion tonnes of coal equivalent (tce) per year by 2020 (assuming an average annual growth rate of 1.5% from 2013 to 2020), with a cap on the share of coal of 62% by 2020 (assuming an average annual growth rate of 0.4% from 2013 to 2020) (IEA, 2016a).

Additionally, in April 2016, the National Energy Administration published the 'Guidance on 2016 Energy Development', which caps 2016 coal production to ~3.65 billion tonnes per year and sets a target to reduce the share of coal in energy mix to below 63% (Zhu, 2016). The Action Plan on Prevention and Control of Air Pollution, issued in December 2013 includes a cap on coal consumption of a maximum of 65% of total annual energy consumption by 2017 in three key regions: Beijing-Tianjin-Hebei; Yangzi River Delta; and Pearl River Delta. The Plan also aims to reduce coal consumption, ban construction of captive coal-fired power plants and prohibit the approval of new coal-fired power generation projects except for CHP projects. This illustrates the complexity of Chinese policy on coal, and shows that there are a number of action plans, policies and instruments, which frequently overlap and can be applied at either the national or regional level.

New NOx and SOx pollution control standards for coal-fired power plants were issued in 2011 (*see* Table 6). In general, these standards are comparable to, and in some provinces even more stringent than, those in the EU and the USA. New plants had to meet the standards from January 2012, whereas existing ones had to comply by July 2014.

Table 6 Pollution standards for coal-fired plants in China (excluding 'priority regions and eastern regions of China) (IEA CCC, 2015a)

Pollutant	Conditions for application	Permitted emission levels (mg/m^3)
Particulates	All	30
SO_2	New unit	100
		200*
	Existing unit	200
		400*
NOx (as NO_2)	All	100
		200*
Hg and compounds	All	0.03

* values are for plants with high sulphur coal and for plants built before 2004

For priority regions, the emissions from all power plants were set as follows: 20 mg/m^3 for PM, 50 mg/m^3 for SO_2, 100 mg/m^3 for NOx and 0.03 mg/m^3 for Hg. For the eastern region of the country, the emissions from new coal power projects must meet the emissions limits for a natural gas-fired gas turbine plant of 10 mg/m^3 for PM, 35 mg/m^3 for SO_2, 50 mg/m^3 for NOx and 0.03 mg/m^3 for Hg.

Design standards for existing and new pulverised coal fired power plants are summarised:

- since 2006, new plants must be SC or USC and 600 MW capacity or larger;
- from 2015, the unit capacity of new coal power projects, must be at least 600 MW USC and mostly 1000 MW USC. Net coal consumption should be lower than 285 gce/kWh and 282 gce/kWh respectively;
- by 2020, the average net coal consumption for all existing coal power plants on a company-by-company basis must be lower than 310 gce/kWh, and all units of 600 MW and more should have a specific net coal consumption of less than 300 gce/kWh;
- since 2004, all new coal-fired power plants should have particulates removal and desulphurisation systems installed; and
- since 2014, in urban areas where there are potential markets for heat, combined heat and power (CHP) plants with unit capacity of 300 MW should be built whenever it is possible.

Standards for the new CHP and CFB coal power plants have also been tightened, but to a lesser degree:

- for CHP units, supercritical steam parameters should be adopted in principle, dependent on overall capacity;
- for CFB units that are 300 MWe or larger, supercritical steam parameters should be adopted in principle; and
- for CFB units burning low-grade coal, the design specific coal consumption must not be more than 310 gce/kWh, or 303 gce/kWh for CFB units that are 600 MW CFB and above.

The 'Notice on Issues Related to Support Policy on the Implementation of Ultra-Low Emission Coal Power Plant Electricity Price' was issued in December 2015 to incentivise the deployment of HELE technologies, as reported by Zhu (2016), The Notice introduces feed-in tariffs for electricity generated from ultra-low emission coal-fired power plants (emission values of PM, SO_2 and NOx: ≤10 mg/m^3, 35 mg/m^3, 50 mg/m^3, respectively). For ultra-low emission coal power plants commissioned before 1 January 2016, the feed-in tariff is subsidised by 0.01 ¥/kWh, while for those commissioned after 1 January 2016, the tariff is subsidised by 0.005 ¥/kWh.

3.4.2 Future trends

Although the full extent of various policies, laws and regulations on the future fleet is uncertain, there are some evident trends:

- smaller, older plants will continue to be replaced by more efficient units;

- the distribution of coal-fired plants will be limited in urban areas, whereas there may be growth in coal consumption in northern and western provinces;
- the increase in coal-fired power generation will be slower and followed by a peak; and
- carbon emission trading programmes and a carbon trading market will be introduced more widely.

Stricter emission limit values will be mandatory for all coal-fired boilers by 2020. China has taken substantial measures to improve its power fleet efficiency and introduced a number of measures such as the Large Substitutes Small programme. The government is currently in the process of developing its 13th FYP, the Master Plan of which will most likely be announced in mid-2017. Consequently, it is unclear yet what targets will be set for energy development and emissions control for the next five years (2016-2020) (Zhu, 2016). However, the 'Action Plan on Upgrade and Reconstruction of Coal-Fired Power Plants for Energy Conservation and Emission Reduction (2014-2020)' issued in 2014, set a target to close inefficient power plants with a total capacity of 10 GW by 2020. The 'Work Program of Full Implementation of Upgrade and Reconstruction of Coal-Fired Power Plants for Ultra-low Emissions and Energy Conservation' issued on 15 December 2015, has a goal to shut down units with a total capacity of 20 GWe or more during the 13th FYP period (2016-2020). The Work Program also outlines measures to provide financial support, electricity price subsidies and the allocation of more utilisation hours (in general, 200 hours) to generators with high efficiency and ultra-low emission power plants (Zhu, 2016). These measures combined support the IEA (2016) statement that it can be expected that coal-fired units of 100 MW or smaller will not be operational in China in the 2020s, whereas most units smaller than 600 MW will not operate for longer than their technical lifetime of 30 years.

In order to reduce local air pollution in urban, heavily populated areas, a number of measures and targets have been introduced. For example, the 'Action Plan on Prevention and Control of Air Pollution' from December 2013, bans building new power plants in three key regions: Beijing-Tianjin-Hebei, Yangzi River Delta and Pearl River Delta until 2018 (Zhu, 2016). In these areas, construction of CHP burning coal will be permitted, with the aim that the CHP units will constitute 28% of coal-fired electricity generation (IEA, 2016a). Additionally, it has been decided that in Beijing City the coal-fired power plants will be phased out and replaced by natural gas by 2017. Moreover, coal consumption caps for Chinese provinces with goals for 2017 have been set (IEA, 2016a).

The Chinese government has identified five key regions with active coal production, (Mongolia, Ningxia, Shaanxi, Shanxi and Xinjiang), as priority areas for the development of large-scale coal generation. They are all in the North West of the country. Locating coal plants close to the mining sites may help improve public health across the population. However, several of the net coal exporting provinces are those which may have future water limitations.

Coal-fired power generation in China is expected to grow, but at a much lower rate than it did between 2000 and 2013 (IEA, 2016a; BP, 2016). In the BP Energy Outlook (2016), China's demand for coal grows by just 0.2% per year until 2035, down from over 8% per year during 2000-14, and by 2030 it is in decline.

This is broadly consistent with the IEA (2016a) report, which estimates that the average annual growth rate may fall to just 0.6% per year to 2020 and equal no more than 1% between 2020 and 2030. At such a rate, coal consumption for electricity would grow by 11% by 2030 (IEA, 2016a).

Any growth in demand for coal-fired electricity would require new capacity, even at a slow growth rate. However, the introduction of various policies and targets may lead to coal-power generation peaking by 2030, with no new capacity required (IEA, 2016a). It has also been suggested that overcapacity could become real, with some arguing that it is already a concern. For example, according to Kahrl (2016) the existing coal-fired generation capacity at the end of 2014 is likely to be sufficient to meet demand until at least 2020, and probably beyond. Furthermore, Kahrl argues that the continued expansion of coal-fired generation capacity poses a significant financial risk to China's electricity industry. Power Engineering International (2016) also suggests that overcapacity exists and reports that construction of new coal-fired power plants has been suspended in 15 provinces until 2017, while the approval of new projects in as many as 13 provinces and regions has also been stopped until 2018.

In September 2015, the Chinese President announced that China will start its national emission trading system, covering key industry sectors in 2017. In 2013 as a preliminary, a carbon emission trading pilot programme was launched in five cities (Beijing, Chongqing, Shanghai, Shenzhen and Tianjin) and two provinces (Guangdong and Hubei). Each of the areas has a different carbon trading model, which should help the best mechanism to be chosen for the national scheme. More information on the pilot scheme can be found in Qi and Cheng (2015).

China has introduced a number of measures aimed at improving energy efficiency and reducing emissions. For example, in 2014: 'Action Plan on Energy Development Strategy (2014-2020)' and 'Action Plan on Upgrade and Reconstruction of Coal-Fired Power Plants for Energy Conservation and Emission Reduction (2014-2020)' were issued. They require comprehensive and systematic upgrades of the 300 and 600 MW-class subcritical and supercritical units in order to achieve the best energy efficiency achievable by comparable plants, as well as conversion of plants of capacity up to 200 MW to CHP by 2020. Also, the existing units of ≥300 MW and captive power generating units of ≥100 MW located in Eastern China should meet the emission standards for gas-fired plants after upgrade (5, 30 and 50 mg/m^2 for PM, SOx and NOx respectively). However, 'Work Program of Full Implementation of Upgrade and Reconstruction of Coal Fired Power Plants for Ultra-low Emissions and Energy Conservation' issued on 15 December 2015, rescheduled the two previous Plans. Consequently, provided the power supply is secured, the upgrading and reconstruction of coal-fired power plants in Eastern China should now be completed by 2017, and all coal-fired utility units of ≥300 MWe and captive power generating units of ≥100 MWe should be upgraded to ultra-low emission units (emissions of PM, SO_2 and NOx ≤10 mg/m^3, 35 mg/m^3, 50 mg/m^3, respectively). This currently excludes W-flame down-fired and CFB boilers. The upgrade of coal-fired units of ≥300 MWe (excluding W-flame down-fired and CFB boilers) in Central China should aim to be completed before 2018 and those in Western China should aim to be completed before 2020 (Zhu, 2016).

3.5 Summary

While expanding its coal-fired fleet capacity, China has taken a number of actions to ensure that the new fleet runs at a high efficiency with a reduced impact on the environment. Many small, inefficient units have been closed and others modified to increase their efficiency. Consequently, China's fleet has an average operational efficiency of 38.6% (LHV), which exceeds the average across coal-fired plants in the IEA member countries (IEA, 2016a). Once an importer of coal technologies, now China competes with Japan in exporting its advanced technologies and continues to invest in R&D in the sector. For example, the double-reheat Guodian Taizhou II unit 3, which was domestically designed, manufactured and built, has reached an efficiency of 47.82% (net, LHV), the highest in China and in the world for a double-reheat coal-fired power plant (Zhu, 2016).

China's environmental standards for new power plants are among the most stringent in the world. This translates to each power plant being equipped with PM and sulphur control equipment, and 95% plants also have nitrogen oxide removal devices (Wang, 2016). Additionally, coal-fired plants in the priority regions have emissions as low as those of gas-fired power plants. Moreover, all coal-fired plants will have to have ultra-low emissions by 2020 (Zhu, 2016).

Strong policies and tight performance standards, combined with the availability of finance for coal-fired projects as well as subsidies for energy generated from ultra-low emission power plants are the main drivers for the implementation of advanced clean coal technologies in China.

Potential and existing overcapacity in some regions, and competition for limited water resources in others, as well as the rapid development of renewables which can reduce the profitability of coal-fired power plants are the main barriers to building new coal-fired plants, even those with state-of-the-art technologies. (Zhu, 2016; Power Engineering International, 2016).

4 European Union (EU)

The EU depends on fossil fuels for most of its energy generation. Currently, coal accounts for about a quarter of all electricity production (EC, 2016b). However, the coal share in the energy mix of the individual Member States varies enormously, from less than 1% in Sweden to over 80% in Poland (EURACOAL, 2012). Similarly, there are significant differences in the coal fleets across the member countries. The average coal-fired power plant efficiency is 38% (LHV, net) (VGB, 2012). A significant proportion of the EU coal fleet is relatively old, as assets over 30-years old account for 38% in EU 15, and 62% in EU11 (central Europe region) (Buisseret, 2016). However, the EU is also home to some of the most advanced coal-fired plants. These include: Maasvlakte 3 in Netherlands which achieves an efficiency of 47% (net, LHV) and RDK8 plant in Karlsruhe, Germany, which holds the current world record for the single reheat coal-fired power plant efficiency – 47.5% (net, LHV) (Santoiani, 2015; Blankenspoor, 2015; Keller, 2016).

4.1 Profile of existing coal fleet

The profile of the EU fleet, abstracted from Platts database, is shown in Figures 7 and 8 as well as in Tables 7–9. Currently, there are 218 units of 300 MW or more. They have a combined capacity of 109,747 MW, which represents around 65% of the EU's total coal-fired capacity. The majority of the fleet, 68%, are subcritical units. Nearly all the plants (over 93%) were built before 1990. There are 30 supercritical units with 15% capacity share and 22 ultrasupercritical units, which comprise 17% of the EU capacity.

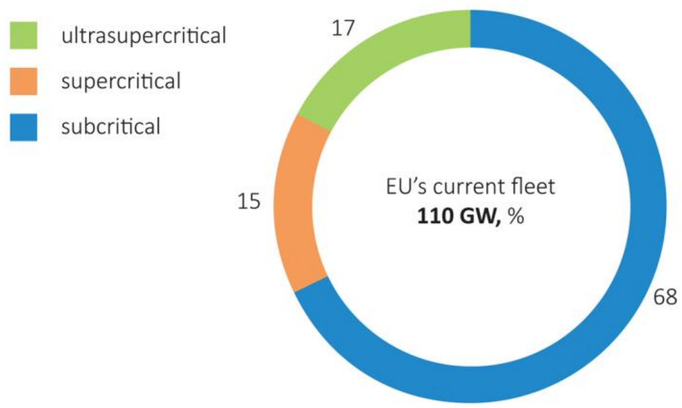

Figure 7 Breakdown of coal-fired fleet in the EU

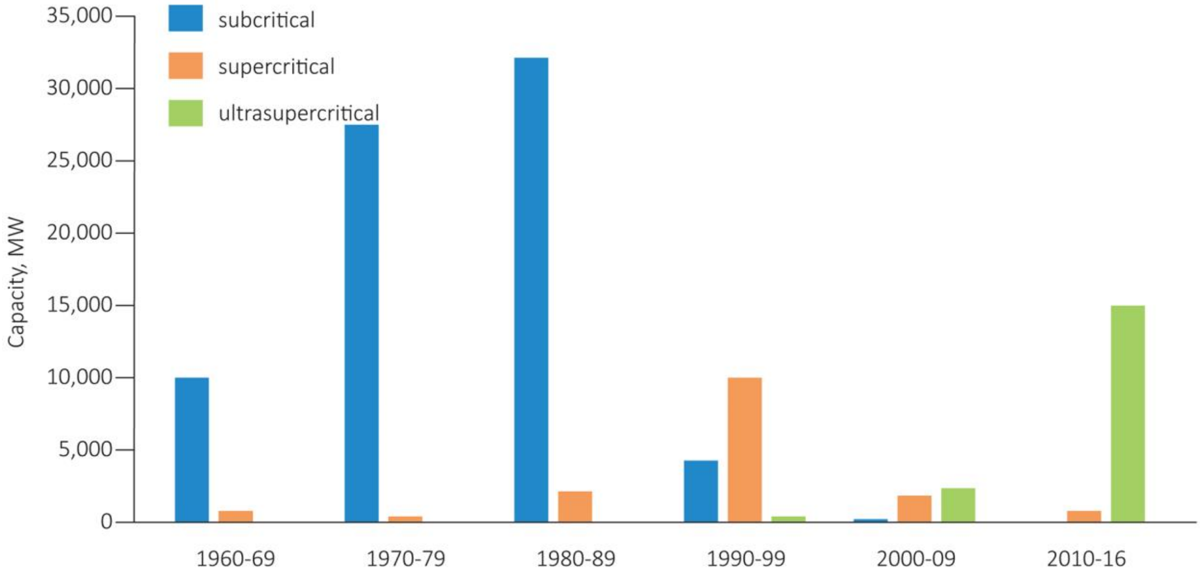

Figure 8 EU coal-fired fleet, by age

The EU has a long history of air pollution regulation and some of the world's most stringent legislation on particulates, SO_2 and NOx emissions. Installation of pollution control technologies began in the 1980s. Consequently, European power plants have a high rate of pollution control technologies installed. As reported by the IEA (2016b), NOx emissions have been reduced by more than 50% and SOx by more than 90% since 1990, while $PM_{2.5}$ emissions have fallen by around 20% since the year 2000. This is despite average annual economic growth of 1.6% since 1990 and a population increase from 478 million in 1990 to 510 million in 2016.

The Large Combustion Plant Directive (LCPD) of 2001, and its successor, the Industrial Emission Directive (IED) introduced in January 2016 have been the main drivers for the installation of relevant pollution control measures.

According to Platts database, 91% of PM control is supplied by ESP systems. Only 4.6% of the plants use either baghouses on their own or in combination with cold-side ESP. One plant uses a multipollutant control technology (SNOX™). There is no information on the systems used in nine plants.

For SOx control, the majority of plants, nearly 88%, have different forms of FGD. The wet limestone type is dominant and is used in about 86% of FGD units. Other types of FGD include: seawater (six plants) and spray dry (four plants) and semi-dry FGD (three plants). Just over 8% of the analysed fleet use compliance fuel (low sulphur fuel).

Less data is available on NOx removal technologies – there is no information on one-third of the analysed power plants. From the data that is available, the majority of plants use low NOx burners (LNB), or LNB combined with other technologies such as separated overfire air (SOFA), overfire air (OFA) and boosted overfire air (BOFA). Around 31% of plants have SCR systems, while just over 4% of plants use flue gas recirculation (FGR) technology for NOx control.

Table 7 Subcritical coal-fired fleet in the EU					
Year of commissioning	**Unit number**	**Size range (MW)**	**Total capacity of the group (MW)**	**Subcritical capacity (%)**	**EU total capacity (%)**
1960-69	24	300–600	10239	13.7	9.33
1970-79	62	300–770	27613.5	36.9	25.16
1980-89	70	300–911	32203.7	43.0	29.16
1990-99	12	310–550	4498	6.0	4.10
2000-09	1	340	340	0.5	0.45
Totals	169		74894.2	100	68.39

Table 8 Supercritical coal-fired fleet in the EU					
Year of commissioning	**Unit number**	**Size range (MW)**	**Total capacity of the group (MW)**	**Supercritical capacity (%)**	**EU total capacity (%)**
1960-69	2	350–600	950	5.68	0.87
1970-79	1	354	354	2.12	0.32
1980-89	5	375–500	2199	13.15	2.00
1990-99	17	347.5–933	10167	60.81	9.26
2000-09	4	330–933	2192	13.11	2.00
2010-16	1	858	858	5.13	0.78
Totals	30		16720	100	15.24

Table 9 Ultrasupercritical coal-fired fleet in the EU					
Year of commissioning	**Unit number**	**Size range (MW)**	**Total capacity of the group (MW)**	**Ultrasupercritical capacity (%)**	**EU total capacity (%)**
1990-99	1	440	440	2.43	0.4
2000-09	3	660–1012	2579	14.22	2.4
2010-16	18	660–1120	15114	83.35	14.1
Totals	22		18133	100	16.91

Maasvlakte Power Plant 3 in Rotterdam, Netherlands, shown in Figure 9, is an example of an EU flagship power plant. Owned by Uniper (formerly part of E.ON), the ultrasupercritical unit started operation in May 2016. It has a capacity of 1100 MW and efficiency of 47% (net, LHV), can cofire up to 30% biomass, is carbon capture ready and can supply district heat (Blankenspoor, 2015). The plant's steam cycle conditions are: 600°C (main) and 620°C (reheat) temperature and 28.5 MPa. The unit has low-NOx burners and is equipped with FGD, SCR and ESP. Consequently, its maximum pollution emission levels are: SO_2 – 40 mg/m^3, NOx – 65 gm/m^3, and PM – 3 mg/m^3. However, on average, emission levels are even lower: SO_2 – 5-25 mg/m^3, NOx – 60–65 gm/m^3 and PM – 1–2 mg/m^3 (Nederveen, 2016). These levels are well below the limits required by the IED. Additionally, the plant uses fuel flow control systems – PROMECON'S MECONTROL Air and MECONTROL Coal, which contribute to more efficient combustion, as well as MECONTROL UBC technology for the fly ash control (PROMECON, nd). Maasvlakte is located on the coast, so it uses seawater for cooling (Blankenspoor, 2015). The unit will take part in the Dutch CCS pilot project known as ROAD (Rotterdam Carbon Capture and Storage Demonstration Project) which is expected to begin operation in 2019. The pilot project will capture around 1.1 MtCO_2/y from the plant over three years. An amine-based-process will be used to capture CO_2, from a slipstream of about 23.4% of the flue gases, at a 90% capture rate (Global CCS Institute, 2016a). After purification and compression, the CO_2 will be transported to storage sites in depleted gas fields, approximately 8 km offshore. In the future, the combination of CCS and cofiring biomass means that the plant is expected to achieve CO_2 emission levels as low as those of a gas-fired power plant (Energy Hub West, 2016; Nederveen, 2016). More information can be found at: http://www.energyhubwest.nl/energy-hub-west.

Figure 9 Maasvlakte Power Plant 3 in Rotterdam, Netherlands (Nederveen, 2016)

Another example of state-of-the-art coal-fired power plant is the RDK8 unit (*see* Figure 10) at the Rheinhafen-Dampfkraftwerk electrical generation facility in Karlsruhe, Germany (Kluger and others, 2016). In operation since 2014, the ultrasupercritical plant has a capacity of 912 MW and operates at 600°C (main) and 620°C (reheat) steam temperature and 27.5 MPa. The unit also supplies district heating. According to Keller (2016), during last winter (2015/2016), the plant achieved an efficiency of 47.5% (net, LHV) which is believed to be the world record for a single-reheat coal-fired power plant. Additionally, connecting the plant to Karlsruhe's district heating system lifted the plant's fuel utilization rate to more than 60%.

Figure 10 RDK8 power plant in Karlsruhe, Germany (Keller, 2016)

4.2 Coal fleet under construction and planned

According to Platts, there are currently seven plants in various stages of construction. All of them are ultrasupercritical plants and their combined capacity is 7645 MW. Five of them are in Poland, one in Germany and one in the Czech Republic.

There are also seven plants planned, with a total capacity of 5768 MW. Five of the planned plants are in Poland, one is in Greece and one in Germany. However, it is highly uncertain if the planned plants will be built and what technology they will deploy. Furthermore, according to Then (2016) there are currently no plans to build a coal-fired power plant in Germany.

4.3 Research and development

There have been several European research projects which focus on advanced materials for AUSC plants. These projects include: The Advanced (700°C) PF Power Plant Project (AD700), Nickel Based Alloys for Operation of 725°C Steam Plants (NIBALO 725), the Component Test Facility (CTF) for a 700°C Power Plant (COMTES 700), and its successor– COMTES 700+ (Di Gionfrancesco and others, 2014; Henderson, 2016).

The COMTES 700 project was financed from the Research Fund for Coal and Steel (RFCS) and jointly sponsored by an international consortium of major European power plant operators and suppliers. The consortium included: Dong Energy Generation, E.ON, EDF, Electrabel, EnBW, PPC, RWE, Vattenfall Europe Generation, Vattenfall Nordic and Alstom, Hitachi-Power Europe, Burmeister & Wain Energy, Siemens. The project was co-ordinated by VGB PowerTech. The total investment amounted to more than €15 million. The objective of the project was to design in detail, manufacture, build and operate the CTF. The facility allowed the testing of the following components: evaporator; turbine valve; superheater tubes; high pressure headers; high pressure piping; high pressure bypass, and safety valves. Operation of the Component Test Facility started in E.ON power plant, Scholven, Germany, in July 2005. It operated for more than 20,000 h until 2009. Materials were tested at 630°C (creep test loop 1) and 725°C (creep test loop 2) (MPA, 2013). More information can be found at: http://www.comtes700.org/index.xhtml. This research has continued under the COMTES 700+ programme, which is an overall umbrella for the following projects: European Network for Component Integration and Optimisation (ENCIO) and Examination of operational and failure behaviour of thick-walled components for high efficient power plants (HWT II) and HWT III (Di Gianfrancesco and others, 2014; Kluger and others, 2016).

The ENCIO project started on 1 July 2011 and was expected to finish in 2017. However, it was terminated in 2014. The focus of the project was on practical investigations, aiming to prove manufacturing, welding, repairs and life-time concepts for thick-walled components (ENCIO, nd). More detail on the project's objectives can be found at: http://www.encio.eu/home.html. One major goal was achieved – the successful manufacture and testing of test components but due to changes in market conditions the planned test facility in Fusina, Italy, was not built (Then, 2016). This programme was funded by RFCS and had a budget of €24.3 million (MPA, 2013).

The HWT II project started in January 2011 and finished in 2014. The project was financed by the industry and the German Federal Ministry of Economics and Technology's COORETEC funding initiative and had a budget of €17.6 million. It included the installation of a test facility at the GKM power plant in Mannheim, Germany. The project was focused on scientific investigation, and aimed to model the material and component behaviour and to validate the results with specific designed component tests. Cyclic start-up and shut-down loading caused thermo-mechanical creep-fatigue in the material, providing valuable information on the failure behaviour of components in a flexibly operated power plant (VGB, nd).

The HWT III, a continuation of HWT II, started in mid-2016 and is expected to end in 2020. It has a total budget of €9 million, which comes both from COORTEC (50%) and various companies including: GE, University of Stuttgart (MPA), GKM, GEBD, GEPD, RWE, EnBW, E.ON, Vattenfall, EVN, KAM, SMST, BGH, KSB and Vallourec. The main objectives of the project include:

- installation of new materials in the existing HWTII test loop;
- testing of new materials in cyclic (620°C–380°C–620°C) and static operation (725°C);
- implementation of new materials (HR6W) for valve makers;
- application of thermal and oxidation resistant coatings to materials; and
- implementation of new AUSC material candidates (Power Austenite and others) into superheater loop (Kluger and others, 2016).

The Nickel Based Alloys for Operation of 725°C Steam Plants (NIBALO 725) project is another example of R&D work co-funded by RFCS (>60%) and industry. It has a total budget of €2.8 million and was expected to start in September 2016 and last for four years. The project consortium includes: GE, Uni Stuttgart (MPA), Centro Sviluppo (CSM), CERTH, GKM and Special Metals. The main objectives of the project are to:

- manufacture thick- and thin-walled samples and components;
- characterise with metallographic methods the qualification of the welds together with mechanical technological tests. Investigate material samples, including welds, under high temperature and load;
- apply and improve numerical models in order to describe the stress-strain behaviour of the material in both thick- and thin-walled components; and
- install and test operation of components in GKM HWT II/III test loop and MPA laboratory under high temperature and load (Kluger and others, 2016).

Another example of R&D work in the EU, is the Power Plant for Future (PP4F) project, which has been in operation since December 2015 and was expected to finish in September 2016. Carried out in Germany, the programme had a total budget of €1.2 million and was cofunded by COORTEC (50%) and industry. The consortium includes: GE, GKM, MPA, GEBD, EnBW, ABB, BPT, FBE, BASF, ZEW, Hochschule Mannheim and TÜV Süd, and FZ Jülich. The aim of the project is to develop and evaluate technical concepts and requirements for high efficient, flexible and low emission coal fired power plant. This includes:

- boiler and turbine design concept development;
- Apros model development and dynamic simulation;
- integration of thermal storage;
- material concept and status of new material qualification; and
- control system adaptation (Kluger and others, 2016).

4.4 Drivers and barriers for implementation of advanced clean coal technologies

Although recent years have shown a fall in final energy consumption and a decrease in the power intensity of the economy, which of course translates into a decrease in coal consumption, historically fossil fuels have had a strong presence in the EU energy mix (Eurelectric, 2015). In 2013, 73% of the EU energy was fuelled by fossil fuels. However, as the EU produces less than 6% of the world's primary energy but consumes over 12%, the block is highly dependent on energy imports. In 2012, 62.5% of hard coal used in the EU was imported (Taylor, 2015). Figure 11 shows the EU and its individual member states' dependency on imported fossil fuels in 2013. The average overall dependency on primary energy imports was 53% for the EU28, although there was much variation. Primary energy is imported from many countries, but the largest proportion of all imported fuels (oil at 34%, gas at 39% and coal 29%) comes from Russia. High reliance on imported coal is partly due to the fact that it is cheaper to import coal than to mine it within the EU.

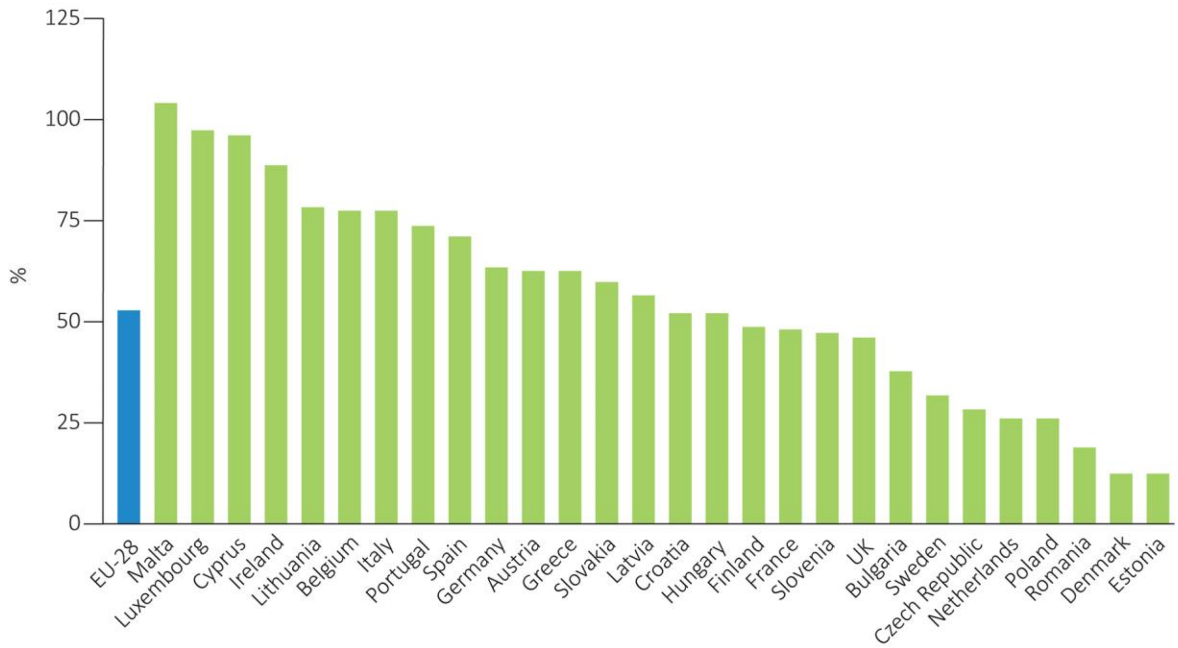

Figure 11 EU dependency on imported primary energy, 2013 (Eurostat, 2015)

Energy was at the forefront of the EU political agenda in 2006. This was due to interruptions to the imported energy supply (Russian gas), volatile oil prices (rising from below 20 €/bbl at the beginning of 2002 to over 70 €/bbl by mid-2006) and the risk of missing the Kyoto Protocol greenhouse gas emissions targets (20% reduction from 1990 levels by 2020 for the EU) (Taylor, 2015). Additionally, there were concerns regarding: blackouts aggravated by inefficient connections between national electricity networks; the difficulties of market access for suppliers in relation to gas and electricity markets and concerns over the production of nuclear energy caused by the Fukushima disaster (Eurostat, 2015). Consequently, the first EU Energy and Climate Policy was agreed in 2007 and ratified by legislation in 2009. The energy policy was built on the three classical pillars: security of supply, competitiveness, and sustainability. Targets were set for the year 2020 for the EU as a whole, which means that they have to be achieved collectively by all EU countries but can vary among the individual Member States. The targets in the 2020 Package, referred as '20-20-20 targets' are: a 20% cut in greenhouse gas emissions (from 1990 levels), 20% of the EU energy to be sourced from renewables and a 20% improvement in energy efficiency (Taylor, 2015). According to the European Parliament (2015), the EU has already exceeded its GHG emissions reduction goals for 2020, having reduced CO_2 emission by 23% between 1990 and 2014. This is despite an increase in the population of more than 30 million (Eurostat, 2016).

Significant progress has been made to increase the share of renewables in the EU energy mix. It has risen from 8.7% in 2005 to 15% in 2013, so the 20% target appears achievable. As noted by Taylor (2015), most countries appear to be reasonably well on track – but some, in particular the UK and the Netherlands, appear to be falling well below the target.

In spite of progress on efficiency improvements, the Commission now estimates that improvements will only total 17.6% by 2020. This is despite the much lower than expected demand brought about by the financial crisis and recession, which according to Taylor (2015) possibly accounted for one-third of the expected improvement.

The EU Emissions Trading System (ETS) is the main policy instrument to reduce GHG emissions. By putting a price on carbon, the ETS is designed to try and bring about the necessary innovation and technology change in the most cost-effective manner (Taylor, 2015). It covers about 45% of EU total GHG emissions. It is a 'cap and trade' system, which means that an emissions cap is agreed for some date in the future and a number of allowances for carbon emissions are sold to plants that emit CO_2. The number of allowances sold decreases annually at a rate fixed (currently 1.74%) to achieve the emission reduction target (cap). The majority of allowances are auctioned. Eighty-eight per cent of those are allocated to states on the basis of their share of verified emissions from EU ETS installations in 2005. Ten per cent of the allowances are allocated to the least wealthy EU member states as an additional source of revenue to help them invest in reducing the carbon intensity of their economies and adapting to climate change. The remaining 2% is given as a 'Kyoto bonus' to nine EU member states which by 2005 had reduced their greenhouse gas emissions by at least 20%from levels in their Kyoto Protocol base year. These are Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania and Slovakia (EU, 2013). The EU-wide cap on emissions is going to increase by 2.2% per year after 2020 and a progressive shift towards auctioning of allowances in place of cost-free allocation is planned (Taylor, 2015; EU, 2013).

In January 2014, the European Commission put forward a further set of energy and climate targets to encourage private investment in infrastructure and low-carbon technologies. These targets have been agreed as follows: at least a 40% cut in greenhouse gas emissions (from 1990 levels) by 2030, a minimum of 27% of EU energy to be supplied from renewable sources and at least a 27% improvement in energy efficiency (Eurostat, 2015). The targets were set with a view to reform the ETS and to consider further amendments to the energy efficiency directive.

A minimum of a 40% reduction in greenhouse gas emissions from 1990 levels by 2030, is the EU's Intended Nationally Determined Contribution (INDC) towards a new universal climate agreement. The EU submitted its INDC on 6 March 2015, well ahead of the United Nations (UN) climate conference (COP 21), as one of the first Parties to do so (European Parliament, 2015). This target means that sectors covered by the ETS will have to have achieved a reduction in GHG emissions of at least 43% (Taylor, 2015).

In 2014, a 2030 Framework for Climate and Energy and the European Energy Security Strategy were decided. Building on these, the Commission has now proposed an Energy Union. An important step in realising this ambition has been the adoption of 'A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy' on 25 February 2015. The strategy has five pillars: energy security, solidarity and trust; a fully-integrated internal energy market; energy efficiency, decarbonisation of the economy, emissions reduction and research, innovation and competitiveness (Eurelectric, 2015; Zuberec, 2015).

Looking beyond 2030, the EU has a long-term goal to reduce greenhouse gas emissions by 80–95% by 2050 compared to 1990 levels. For the industrial sector this will require an 83–87% reduction (EC, 2016c). As noted by Taylor (2015), for the power sector the GHG emission reduction will have to be between 93–99%. Additionally, intermediate cuts of 25% by 2020, 40% by 2030 and 60% by 2040 would be needed. This effectively means that after 2030, all coal-fired coal plants will have to be equipped with carbon capture or will be driven out of the energy mix.

The EU aims to achieve its energy decarbonisation targets while increasing competitiveness and security of supply. However, this can only happen if there are significant investments in new low-carbon technologies, renewable energy, energy efficiency and grid infrastructure. As investments are made for a period of 20 to 60 years, policies that promote a stable business climate which encourages low-carbon investments should be made (EC, 2016c). The European Commission set a Roadmap for building a competitive low-carbon Europe by 2050 to facilitate these policies. The document outlines plausible ways to achieve the 80% reduction target from a broad European perspective. Detailed information can be found at http://www.roadmap2050.eu/

Progress on CCS in the EU has been slow and industry has found little incentive to invest in CCS for coal-fired plants as pollution permits in the EU ETS are too cheap, currently stuck at around 5 €/t in an oversupplied market (Reuters, 2016a). However, assuming that the EU's climate targets will be implemented, CCS is the only option for coal-fired plant operators which wish to continue to run after 2030. According to Reuters (2016a), although industry has been reluctant to invest in its upfront cost, it is beginning to realise that CCS may be a cheaper option than abandoning assets.

Legislation and energy and climate related policies can be both a driver and a barrier to implement clean coal technologies in the EU. For example, in 2015 the UK Government announced the closure of all unabated coal-fired power plants by 2025. As CCS is not yet commercially available, no one would build a plant now knowing that it would not be able to operate after 2025. In contrast, in Poland, the Government (Tchorzewski, 2016) recently announced that it will invest between 35–55 billion zlotys (up to €12.5 billon) in coal-fired power plants. The decision is motivated by the fact that energy from coal is more secure and economically feasible under Polish conditions. The projects will start before 2025. Hence all current coal-fired power plant which are under construction and planned are likely to be completed. In Germany, where about 44% of electricity comes from coal, the government plans not only to increase the share of renewables, but to phase out nuclear (in 2022) and coal-fired plants (after 2050) (PEI, 2016).

The European Commission has introduced and funded various programmes to assist the implementation of clean coal technologies (CCT) and carbon capture and storage (Zuberec, 2015). They include:

- 7th Framework Programme: an estimated €200 million has been spent on CCT and CCS (2007-2013);
- European Economic Recovery Plan (EERP): €1 billion was made available (from 2008);
- NER 300: funding for the projects that demonstrate technologies that will subsequently help to scale-up production from renewable energy sources across the EU as well as those that can remove

and store carbon emissions. Funding comes from revenues resulting from the sale of emission allowances in the EU ETS. Nineteen projects were awarded funding of €1 billion;

- Horizon 2020: up to around €35 million can be used to co-fund fossil fuel related research with CCS as the main focus; and
- Research Fund for Coal and Steel (RFCS): an estimated €14 million annually can be used to co-fund coal projects (roughly €200 million has been spent on coal projects since 2003).

As reported by Zuberec (2015), the European Commission has made €2 billion available for CCS projects alone.

However, there are a number of barriers to the implementation of advanced clean coal technologies. These include: legislation which allows subsidies for renewables as well as plentiful supplies of gas, the falling cost of renewables, and prioritising the feed of renewables into the grid. In combination they make coal plant less profitable and under pressure to meet environmental standards while running with smaller capacity factors. In addition, ambitious GHG reduction targets in combination with low carbon prices under the ETS and the consequent absence of CCS are a major barrier.

4.4.1 Overview of policy and regulatory framework

The Industrial Emissions Directive (IED) is the main EU instrument that regulates pollutant emissions from coal-fired power plants (EC, 2016a). The directive is based on several pillars, specifically: an integrated approach; the use of best available technologies; flexibility; inspections and public participation. Power plants are required to operate in accordance with a permit granted by authorities in the Member States. The permits contain conditions set in accordance with the principles and provisions of the IED.

The integrated approach means that the permits must take into account the whole environmental performance of the plant, including emissions to air, water and land, the generation of waste, the use of raw materials, energy efficiency, noise, prevention of accidents, and restoration of the site upon closure.

The permit conditions include emission limit values which must be based on the Best Available Technologies (BAT). BAT are those which allow a high general level of protection of the environment to be achieved and are both economically and technically feasible. Additionally, BAT refer to the way that an entire installation is designed, maintained, and operated (EPPSA, 2015). BAT and the BAT-associated environmental performance at EU level are defined in BAT Reference Documents (BREF). Current BREF set limits for NOx, SOx and PM for power plants depending on their capacity and age. For example, the following limits (daily average) apply to hard coal-fired power plants with a capacity of 300 MW or more:

- PM – 20 and 10 mg/m^3 for existing and new power plants, respectively;
- SO_2 – 200 and 150 mg/m^3 for existing and new power plants, respectively; and
- NOx - 200 and 150 mg/m^3 for existing and new power plants, respectively.

More detailed information can be found in IEA CCC emission standards database: http://www.iea-coal.org.uk/documents/83365/9582/European%20Union

Authorities which grant permits have some flexibility and can establish less strict emission values for a specific plant and issue some derogations. However, this is possible only in cases where an assessment shows that achieving the emission levels associated with BAT would lead to disproportionately higher costs than the potential environmental benefits due to the geographical location or the local environmental conditions or the technical aspects of the installation.

Additionally, the IED requires mandatory environmental inspections of the plant under the permit, which should be set up by the Member States and include a site visit at least every one to three years.

Finally, the IED allows the public to participate in the decision-making process, and to be informed of its consequences, by having access to permit applications, permits and the data from the monitoring of releases (EC, 2016a).

Current emission standards under the IED have been revised recently and new limits have been proposed. They are included in a working draft BREF for large combustion power plants, published by the European IPPC Bureau (of the Commission's Joint Research Centre) in June 2016 and available at: http://eippcb.jrc.ec.europa.eu/reference/BREF/LCP_FinalDraft_06_2016.pdf. Stricter emission levels for NOx, SOx and PM (BAT-AELs, associated emission levels, daily averages), have been proposed for pulverised coal-fired boilers, depending on factors such as the age of the plant and number of operating hours. The proposed levels for plants larger than 300 MW are:

- NOx, 85–165 mg/m^3 for existing plants and 80–125 mg/m^3 for new plants;
- SO_2, 25–165 mg/m^3 for existing plants and 25–110 mg/m^3 for new plants; and
- PM, 3–11 mg/m^3 for existing plants and 3–10 mg/m^3 for new plants (and for new plants larger than 1000 MW, 2–8 mg/m^3).

Standards based on yearly averages for HCl and HF have been introduced. They depend on the number of operating hours, the age of the plant and whether the plant has a wet FGD with a downstream gas-gas heater. The standards for plants larger than 100 MW are:

- HCl, 1–5 µg/m^3 for existing plants and 1–3 µg/m^3 for new plants; and
- HF, <1–3 µg/m^3 for existing plants and <1–2 µg/m^3 for new plants.

For mercury, the proposed emission standards are between 1 and 10 µg/m^3 depending on fuel type, the plant size and its age. For bituminous coal plants the proposed limits are: 1–4 µg/m^3 for existing plants and 1–2 µg/m^3 for new plants. While for lignite plants the proposed standards are: 1–7 µg/m^3 for existing and 1–4 µg/m^3 for new plants. These proposed standards are for plants larger than 300 MW.

BREF offers some flexibility for older plants, especially for NOx control on plants commissioned before 1987. It should be noted that apart from daily average values the BREF contains yearly averages which are generally lower than the daily limits. The proposed emission limits and the conditions to which they are applied are described in detail in the document which is nearly 1000 pages. Hence the interested reader is referred to the online version (*see the link above*). A vote on the acceptance of the BREF is expected to take place in late 2016 to early 2017. If approved, the BREF should be adopted in 2017 and permits for plants will have to change accordingly within four years of its publication (Sloss, 2016b; EPPSA, 2016).

4.4.2 Future trends

As noted by the European Commission (2011) in the Energy Roadmap 2050 'forecasting the long-term future is not possible'. However, based on the EU's current energy policy, there will be a growing need for flexibility in coal-fired plants and some conversion to biomass firing or cofiring.

The share of renewables in the energy mix across the EU is increasing. Energy from renewable sources is currently prioritised for input into the grid in many countries. Consequently, coal-fired power plants must now provide more flexible output to balance the grid. For example, the capacity factor of fossil fuel power plants decreased by 3% during 2013 and 2014. Coal-fired capacity factors decreased by about 5% over the same period and currently have a value of around 53–54% (Eurelectric, 2015). This means that coal-fired plants are operating for fewer hours.

Flexible operation puts strain on the operation of coal-fired power plants and investment may be required for plant upgrading, technical development and even modification of plant operating practice in order to improve their flexibility (Sloss, 2016a).

Some coal-fired plants may be mothballed or decommissioned due to the environmental legislation but also as a result of low wholesale prices and small capacity factors which make it difficult for plants to remain profitable.

As reported by European Commission (2015), the final energy consumption from biomass in the EU28 grew from 72 million tonnes of oil equivalent (Mtoe) in 2004 to 128 Mtoe in 2013. While the total share of biomass among renewable energy sources has remained constant (at 65%) over the past decade, the share of biomass in the overall energy mix has grown from 4% in 2004 to 7.7% in 2013. At the end of 2015, 46% of renewable energy in the EU came from solid biomass (almost exclusively wood). Based on national estimates the European Commission expects that the supply of biomass for heating and electricity will continue to increase further to 132 Mtoe in 2020. Many EU countries subsidise renewable energy, and support cofiring in coal-fired plants. In some instances, power plants which opted for closure under the LCPD, are in receipt of subsidies to convert into biomass-fired units. For example, Lynemouth power plant in the UK (3 x 140 MW units) closed at the end of 2015 due to a lack of SOx and NOx control, is now being converted to firing biomass. The current plant owner (EPH) applied for a Contract for Difference (CfD) from the UK government and will benefit from 105 £/MWh for 10 years. The project is ongoing and consists of a number of upgrades. These include: a new fuel feeding system, mill modifications and new dynamic classifiers, replacement of existing pulverised fuel pipes for those suitable for a more corrosive environment, new low-NOx bespoke biomass burners, a new boosted overfire air (BOFA) system for further NOx control, upgraded oil system, new dry bottom ash and fly ash systems as well as an ESP upgrade. These modifications will allow the plant to maintain 40% plant efficiency and compliance with the IED emission limits. The commercial operation of the plant is expected to start at the end of 2017 (Welford, 2016).

As mentioned before, mercury can be largely removed from coal-fired power plants in the pollution control devices designed to remove other air pollutants, such as NOx, SOx and PM. Thus more than 90% of mercury is expected to be removed by co-benefit (Sloss, 2015). Currently, the EU does not have mercury emission standards but the new BREF draft document for the IED proposes mercury emission standards of between 1 and 10 µg/m^3 (*see* Section 4.3.1). These targets are challenging and will require mercury specific control systems. Consequently, it is likely that coal-fired power plants will have to deploy mercury specific control technologies and monitoring after 2021). There are a number of such systems already widely deployed in the USA where mercury standards are in place (Sloss, 2012, 2015).

4.5 Summary

The average coal-fired power plant efficiency in the EU is 38% (LHV, net) (VGB, 2012). Although, a significant proportion of the EU coal fleet is relatively old, the EU is also home to one of the most advanced coal-fired plants with a net efficiency of around 47% (LHV) (Santoiani, 2015; Blankenspoor, 2015). As the EU has some of the world's strictest emission standards, pollution control systems for NOx, SO_2 and PM are widely deployed.

While the EU works towards Energy Union and further tightens its environmental regulations for coal-fired power plants and prioritises renewable energy generation, some countries have pledged to reduce or phase out coal-fired power plants. However, despite this and the EU's ambitious climate targets, some member states, notably Poland, will continue to rely on coal. Hence, a few coal-fired plants are still being planned and built.

The EU has ambitious targets to reduce greenhouse gas emissions, 40% by 2030 and by 80–95% by 2050 compared to 1990 levels. Meeting these targets would require all coal-fired power plants wishing to operate after 2030 to have CCS in place. However, despite the availability of significant funds from the European Commission, work on CCS has stalled in the EU. The carbon price under ETS currently is too low to encourage investment in CCS. This is obviously a significant barrier to building new coal-fired plants. Yet, this may change, and a revival of R&D on CCS may be triggered if industries start to realise that investing in CCS may be a cheaper option than abandoning their assets. Additionally, significant R&D work on AUSC plant, shows a commitment to the future deployment of advanced clean coal technologies, possibly in the EU or overseas.

5 Japan

Japan is the global leader in HELE technologies having built the first ultrasupercritical coal plant in 1993. HELE technologies have now been adopted by the majority of its coal plants, and Japan has the highest average efficiency fleet in the world (Lockwood, 2016; IEA, 2016b; Makino, 2016a). Japan's coal fleet consumes around 211 Mt/y of coal and provides approximately 30% of the country's energy supply. All of the coal is imported, mainly from Australia and Indonesia (Sakai, 2015).

5.1 Profile of existing coal fleet

The Japanese fleet comprises 49 units of 300 MW capacity or larger. The combined capacity is 34,600 MW, which represents around 79% of Japan's total coal-fired capacity. As shown in Figures 12 and 13 and Tables 10-12, the coal fleet consists of 57% ultrasupercritical units, 38% supercritical and only 5% subcritical units. It is also relatively young. Ultrasupercritical units have been the dominant technology since 2000.

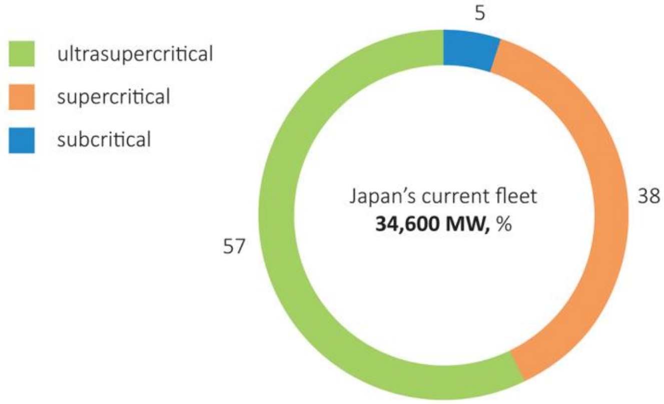

Figure 12 Operating coal-fired fleet in Japan

Figure 13 Japan's coal-fired fleet, by age

Table 10 Subcritical coal-fired fleet in Japan

Year of commissioning	Unit number	Size range (MW)	Total capacity of the group (MW)	Subcritical capacity (%)	Percentage of total capacity (%)
1980-89	2	350	700	41.2	2.0
1990-99	2	350	700	41.2	2.0
2000-09	1	330	300	17.6	0.9
Total	5		1700	100	4.9

Table 11 Supercritical coal-fired fleet in Japan

Year of commissioning	Unit number	Size range (MW)	Total capacity of the group (MW)	Supercritical capacity (%)	Percentage of total capacity (%)
1980-89	9	500–700	5200	39.1	15.0
1990-99	8	500–1000	6200	46.6	17.9
2000-09	3	500–700	1900	14.3	5.5
Total	20		13300	100	38.4

Table 12 Ultrasupercritical coal-fired fleet in Japan

Year of commissioning	Unit number	Size range (MW)	Total capacity of the group (MW)	Ultrasupercritical capacity (%)	Percentage of total capacity (%)
1990-99	8	600–1000	6500	33.2	18.8
2000-09	13	600–1050	10600	54.1	30.6
2010-16	3	600–1000	2500	12.8	7.2
Total	24		19600	100	56.6

Air pollution control in Japan is a high priority, based on a sense of social responsibility. Hence many plants pride themselves on fitting the most up to date systems (Sloss, 2012). By 2000, it was reported that over 90% of plants had wet scrubber systems installed and only 3% had no flue gas treatment technology for sulphur control. Seventy-five per cent of plants had both low-NOx and SCR systems installed and the remainder had either low-NOx or SCR systems (Ito and others, 2006).

Data from Platts shows that around 92% of plants have PM control in place. Of these, 23% have the most advanced control technologies such as low temperature ESP and wet ESP. There is a lack of information on the remaining 8%. All power plants have SOx control, including advanced equipment such as the multipollutant control system ReACT™. Over 81% of plants have wet limestone scrubber FGD. The dominant NOx control technology is SCR (around 71%), installed alone or in combination with low-NOx burners. However, there is a lack of data on about 16% of plants.

Japanese coal-fired plants set a benchmark on many levels. For example, the Isogo coal-fired plant in Yokohama is considered to be the world's cleanest coal-fired power plant in terms of emissions intensity (Santoianni, 2015).

Figure 14 shows the two 600 MW ultrasupercritical units. Unit 1 was commissioned in 2002 and operates at main and reheat temperature of 600°C and 610°C, respectively. Unit 2 was commissioned in 2009 and operates at main and reheat temperature of 600°C and 620°C respectively, achieves 44% gross, 41% net efficiency (HHV) (Makino, 2016a). The average emissions for both units have been reported as: 16.5 mg/m^3 for NOx, 15 mg/m^3 SOx and 7.5 mg/m^3 for PM. However, Unit 2, emits considerably less: single digit-levels for NOx and SO_2 and below 5 mg/m^3 for PM. Emissions are controlled in both units, by a combination of SCR and ESP with a multipollutant removal system – ReACT™. The latter is a regenerative activated coke dry-type capture technology that captures SOx, NOx and mercury while only using 1% of the water required by conventional wet FGD. First, flue gas is treated by an ammonia SCR before entering the ReACT™ system. This combination achieves an average, for both units, of 92% NOx removal. ReACT™also removes around 98% of SO_2 and up to 90% of mercury (Peltier, 2010). Consequently, both units have emissions comparable to that of a natural gas-fired combined-cycle facility (Power Technology.com, 2016). More information on the ReACT™ system can be found in an IEA CCC report by Carpenter (2013).

Figure 14 Isogo coal-fired power plant, Japan (Peters, 2010)

Japan has one 250 MW IGCC unit, at the Nakoso Power Station in Iwaki City, Fukushima. The plant was in demonstration mode from 2004 to 2013, then was damaged in the 2011 earthquake and is currently in full commercial operation. More information can be found at: https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/project-examples.

5.2 Coal fleet under construction and planned

Currently, there are no coal-fired plants under construction. However, according to Reuters (2016b), there are plans to build 45 new coal-fired units, with a total capacity of 20,888 MW, which are due to come online in the next decade or so. Twenty-five of these will have a capacity 300 MW or more. According to Platts database (as of March 2016) there are only 17 units of this size planned with a total capacity of 12,160 GW, 75% of which are reported to be ultrasupercritical units.

So, the exact amount of future coal-fired plant capacity is uncertain. It is possible that the coal share may be higher than the current target for the 2030 energy mix. This could be due to a number of reasons, including that the predicted prices for renewables generation are higher than those of coal (*see* Section 5.3); and that it may be difficult to restore the nuclear share of the energy mix after the introduction of increased security measures. Consequently, coal-fired plants (or other fossil powered ones) may be required to supply more energy. Additionally, if the global price of natural gas price grows by 2%/y, in 2030, the global share of coal-fired plants in the energy mix may double which may also impact the energy mix in Japan. (Makino, 2016c).

5.3 Research and development

Japan is committed to implementing the most advanced clean coal technologies and continues to invest in R&D in this field. This is confirmed by the government's following aims (Barnes, 2014; Sakai, 2015):

- to achieve the practical use of AUSC thermal power generation (generating efficiency around 46% HHV, CO_2 emissions of 710 g/kWh) in the 2020s;
- to achieve the practical use of IGCC power generation systems of 1500°C class in the 2020s (with improved generating efficiency rate of 46% HHV);
- to establish IGCC power generation systems of 1700°C class in the 2020s (generating efficiency 46–50% HHV, CO_2 emissions of 650 g/kWh); and
- to establish the technology of integrated coal gasification fuel cell combined cycle (IGFC) by 2025 and achieve its practical use in the 2030s (approximate generating efficiency rate of 55% HHV, CO_2 emissions of 590 g/kWh).

Japan supports the efficient utilisation of low-grade coal which can be achieved with IGCC technology. Currently there are two projects under development: Nakoso IGCC Power GK and Hirono IGCC Power GK, both 540 MW. Nakoso is due to start operation in 2020, and Hirono in 2021 (Mitsubishi Electric Corporation, 2016).

Japan is also promoting CCS and carbon capture and utilisation (CCU) technology development and demonstration and has a number of projects at various stages of development. These include: chemical looping, CO_2 recycle, oxyfuel combustion, post-combustion capture and CO_2 conversion. For example, oxyfuel combustion is expected to be commercially deployed around 2020, post-combustion capture around 2030, with chemical looping in the early 2030s (Makino, 2016b). The CCS demonstration project in Tomakomai will capture and purify CO_2 from a hydrogen production unit in an oil refinery, before compression and subsequent injection into offshore geological formations. CO_2 injection of 0.1 Mt CO_2/y will take place between 2016 and 2018 (Global CCS Institute, 2016). As acknowledged by Brad Page, the CEO of the Global CCS Institute: 'Japan has demonstrated great leadership on the world stage, and several of the world's 15 operational large-scale CCS projects were made possible with the inclusion of Japanese technology' (Global CCS Institute, 2016).

5.4 Drivers and barriers for implementation of advanced clean coal technologies

Since the Great East Japan Earthquake in March 2011, Japan's energy mix has changed significantly. As shown in Figure 15, nuclear power was replaced mainly by fossil fuel-fired power plants, with coal accounting for 31% of the electricity share in 2014. The increased share of fossil fuels in the energy mix led to elevated CO_2 emissions (*see* Figure 16) as well as an increase in electricity prices (*see* Figure 17). In 2013, CO_2 emissions from electricity utilities were 110 Mt higher than in 2010. Electricity prices in 2014 were 25.2% higher for households and up 38.2% for industry (Yamazaki, 2015).

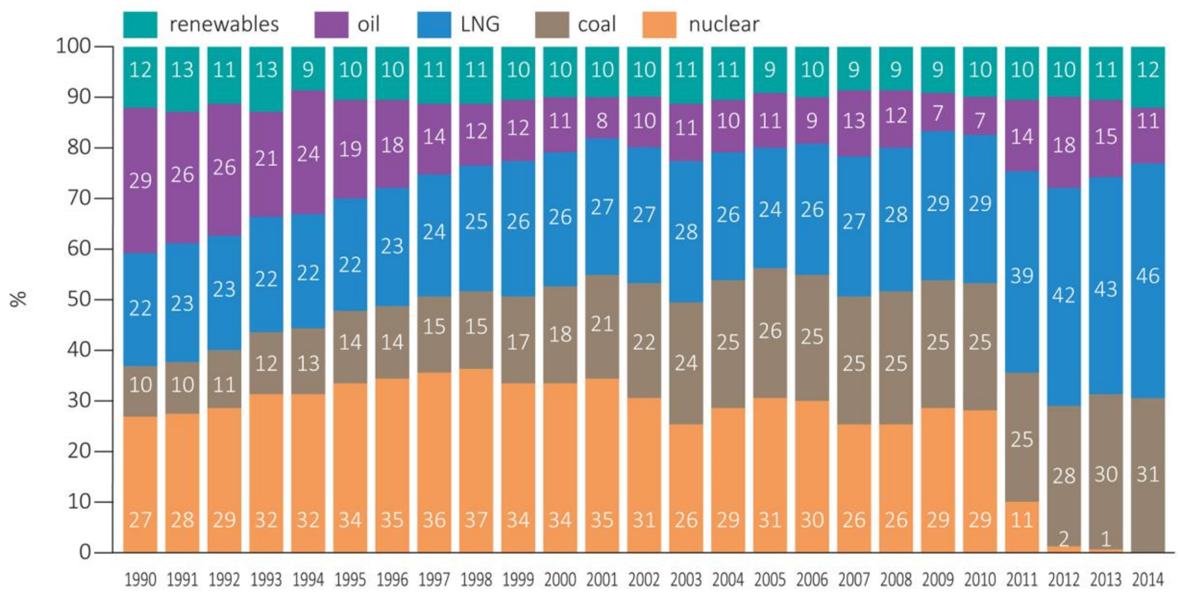

Figure 15 Transition of Japanese energy generation mix after the Fukushima disaster (Yamazaki, 2015)

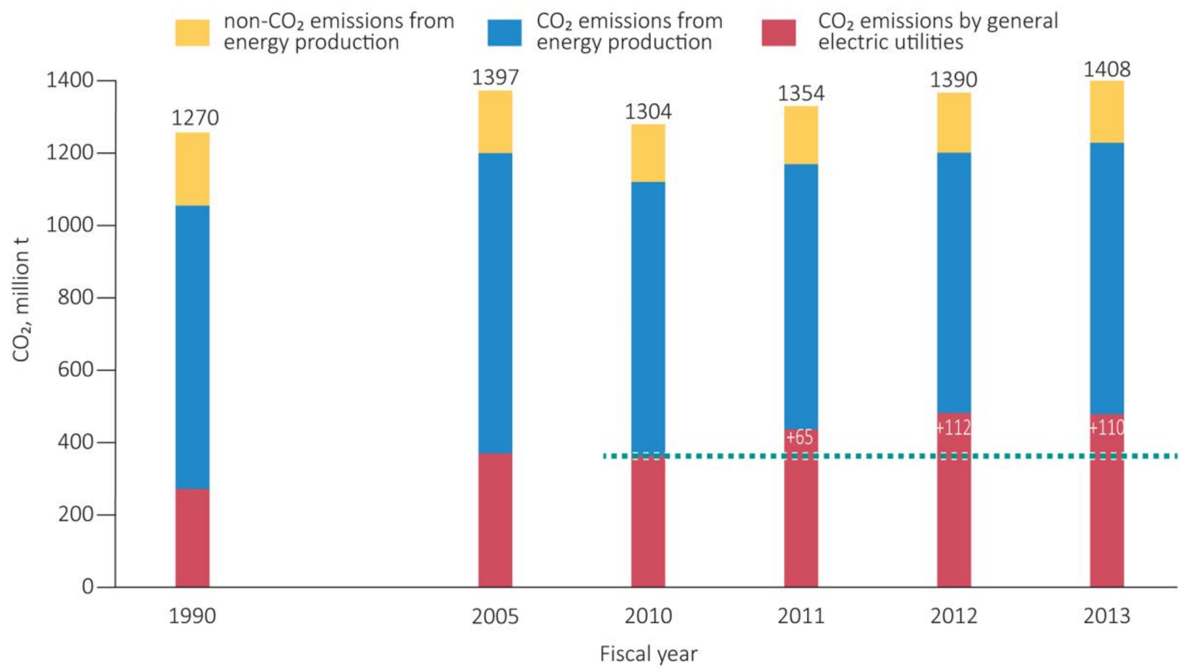

Figure 16 CO_2 emissions increase in Japan after March 2011 (Yamazaki, 2015)

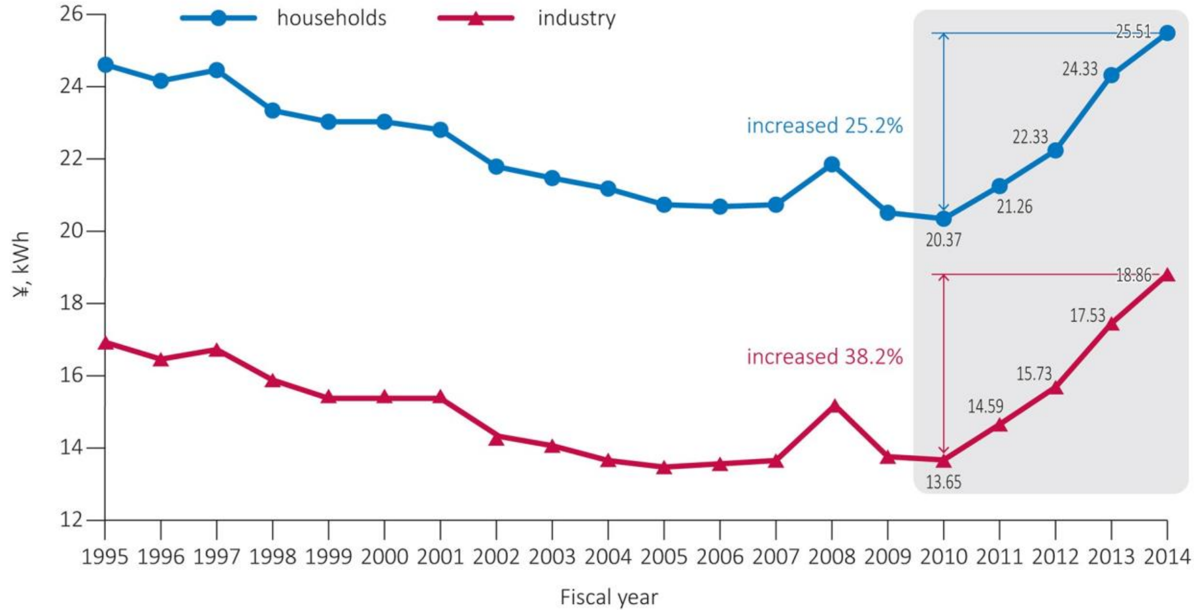

Figure 17 Japan - electricity prices before and after March 2011 (Yamazaki, 2015)

The disaster also revealed negative aspects of the current energy market, which operates as regional monopoly system with 10 large and vertically integrated electricity power companies. There are different energy frequencies in the West (60 Hz) and East (50 Hz) regions and only 1.2 GW can be transmitted between the regions. Hence, the energy market needs to address the following issues:

- lack of a system to transmit electricity between regions;
- little competition and strong price control; and

- limited flexibility in changing the existing energy mix; it is particularly hard to increase the share of renewables (Yamazaki, 2015).

Japan's new energy mix towards 2030 was announced in July 2015. As shown in Figure 18, Japan aims to have 22–24% of renewables, 20–22% of nuclear, 27% of liquefied natural gas (LNG), 26% of coal and 3% of oil. The Trade and Industry Ministry also estimated the per-unit cost of each source of electricity in 2030. According to the predictions, the cost of energy per kilowatt hour will be ¥10.1 for nuclear power, ¥12.9 for coal-fired thermal power, ¥13.4 for LNG thermal power, ¥13.9-33.1 for wind power and ¥12.5–16.4 for solar power (The Japan Times, 2015).

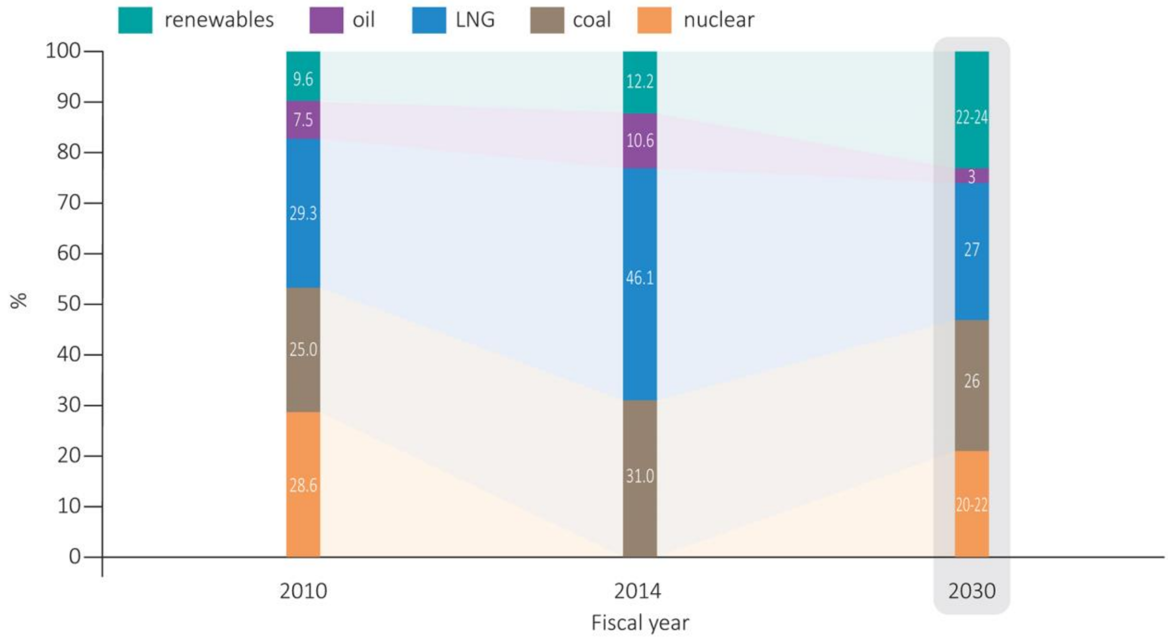

Figure 18 Japanese generation mix and future target (Yamazaki, 2015)

The plan is to increase coal's share in the mix by only 1% more than it was before the Fukushima disaster, which means more coal capacity as part of a secure energy supply (*see* Figure 18). Some argue that the share of natural gas-fired plants could be higher as they emit less pollution. However, Japan's decision to invest in coal-fired plants seems to be justified as the technologies deployed are among the most advanced and electricity from coal generation is cheaper than from other fossil fuels.

However, according to Smith (2015), the energy mix proposed for 2030 may not be realised for various reasons. Following the Fukushima accident in 2011, it was decided that in principle nuclear reactors should be decommissioned after 40 years of operation, except for a one-time extension of up to 60 years if they undergo expensive safety renovations. Another reason is the continuing public concern about the safety of nuclear power, which may affect the building of new reactors. If no new nuclear reactors are built in the preceding years, power companies will be forced to extend the lifetime of older reactors to 2030 to secure a 20–22% share for nuclear energy. This is assuming that all of the reactors approved by the Nuclear Regulation Authority (NRA) have been put back online. According to Smith (2015) this is unlikely to be realised and 'if the government works very hard, perhaps 10 to 12 reactors will come back online. But that is one-fifth of what Japan had before 2011 and certainly not sufficient to provide 20 per cent of Japan's energy needs'. Consequently, the nuclear share in 2030 may be much lower than desired and coal may be required to fill the gap in the energy mix.

Additionally, analysis of the global energy mix by JCOAL shows that if the price of natural gas has increased by 1.5–2%/y to 2030, the coal ratio in the global energy mix then may have increased by 10–40%. A change in coal price is not forecast to have an effect on the proportion of coal in the energy mix (*see* Figure 19). Thus, coal-fired plants in Japan may have an increased share of the 2030 energy mix. However, as utilisation rates of Japan's coal-fired power plants are already greater than 80%, the country would need to expand its coal-fired capacity (EIA, 2015).

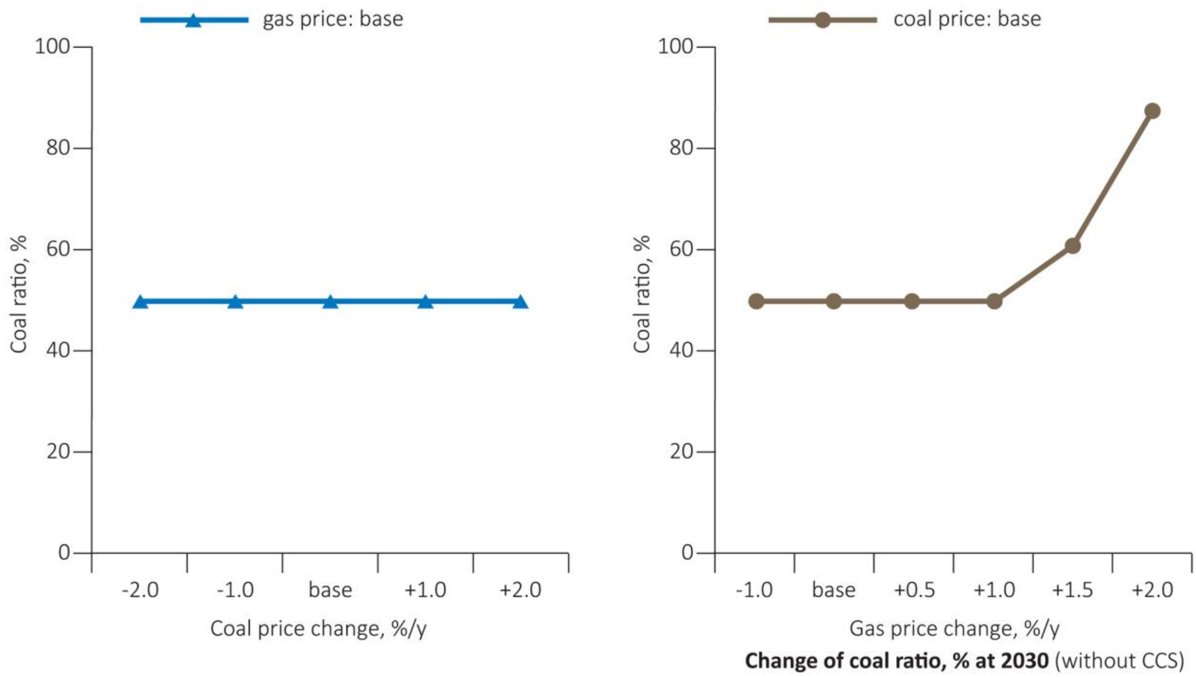

Figure 19 Predicted effect of global coal and gas prices on their shares in the global 2030 energy mix (Makino, 2016a)

Japan aims to reduce CO_2 emissions by 26% from a 2013 base as part of its Intended Nationally Determined Contributions from COP21. Japan plans to achieve this by replacing subcritical and supercritical units with ultrasupercritical technologies and deployment of CCS, as well as by increasing the share of renewables in the energy mix up to 22–24% in 2030.

Thus, the drivers for the implementation of HELE coal-fired plants are: the need for a secure energy supply and diverse electricity mix; the low price of coal and coal-generated energy; a commitment to reducing CO_2 emissions; available funding and the desire to export clean coal technologies to the nations which are adding coal-fired capacity.

However, according to Caldecott and other (2016), there is a possibility that if Japan builds new units, these assets could become stranded assets within 5–15 years with a value of $61.6-80.2 billion. Despite this concern being raised, it appears there are no major barriers to the deployment of clean coal technologies in Japan.

5.4.1 Overview of policy and regulatory framework

Japan's New Energy Mix (Long-term Prospect of Supply and Demand of Energy) towards 2030 was decided in July 2015. Its basic aim is to achieve a balanced energy mix, while achieving 3E+S (Safety, Energy Security, Economic efficiency and Environment). It includes a number of targets:

- a self-sufficiency rate of 25%;
- lowered electricity cost from the current level;
- GHG emission reduction targets the same as the EU and USA;
- ensure economic and stable coal supply by having coal supplied from diverse sources;
- achieve average power generation efficiency of total domestic coal-fired power plants equivalent to 'USC level' by 2030, leading to CO_2 emissions reduction; and
- establish and introduce the next-generation of coal-fired power technologies, such as AUSC and IGCC within 10 years (Fuji, nd).

The Japanese government advocates the use of cleaner coal technologies as it supports the premise that promoting HELE technologies is crucial to achieving energy security while addressing environmental concerns, both domestically and internationally. Japan not only exports its HELE technologies, it also offers financial assistance to countries which are increasing their coal-fired fleets. According to Bast and others (2015), Japan provided the largest annual public financing for fossil fuels – an annual average of $19 billion over 2013 and 2014. Japan also stresses the need to maintain international funding for coal-fired power plants in developing and emerging countries. For example, Japan is helping Ukraine to modernise its ageing coal fleet (Fujii, nd). As a result, it is predicted that Ukraine will lower its dependence on imported gas by 10%, which is important for security reasons (Dodson, 2014). Japanese support of various clean coal technologies is translated into ongoing R&D as described in Section 5.5.

Environmental legislation in Japan is set at a private individual company or plant basis, and hence it is difficult to summarise the requirements that apply (Sloss, 2012). Social responsibility is a high priority, which means that power plant owners install advanced pollution control systems. An overview of the legislation is given in Table 13. More detailed descriptions can be found in the IEA CCC emission standards database http://www.iea-coal.org.uk/documents/82549/9446/Japan.

Table 13 Overview of Japanese pollution standards (IEA CCC, 2015b)

Pollutant	Boiler type	Capacity (m^3/h)	General standard (mg/m^3)	Special standard (mg/m^3)
Particulate matter	Coal boiler*	<40,000	300	150
		≥40,000 <200,000	200	100
		≥200,000	100	50
	Gasifier†		50	30
NOx (as NO_2)	Coal boiler*	<40,000	614	
		≥40,000 <700,000	512.5	
		≥700,000	410	
	Gasifier†		307.5	
SOx (as SO_2)	Emission limit (q) is set on the basis of a constant value K at every designed area and the effective stack height: $q = K \times 10^{-3} \times He^2$			

* heating area >10 m^2; † >coal consumption 20 t/d

5.4.2 Future trends

Based on Japan's current energy policy and proposed New Energy Mix toward 2030 the following future trends are likely:

- replacement of subcritical and supercritical plants by more advanced technologies;
- keeping the diverse supply of coal and promotion of the low-grade coal use in future;
- increased biomass cofiring; and
- development of new advanced coal technologies. Japan promotes the use of low-grade coal so that a greater choice of supply will be available in the future. As it is R&D on IGCC and low-grade coal utilisation technology is progressing, the greater use of lignite can be anticipated in the future.

Currently biomass is cofired at an average rate of 1–3% of in Japan. There is 337,000 t/y of domestic and 400,000 t/y of imported biomass cofired. According to Makino (2016b), the cofiring rate will increase to 5-10% in future, which will correspond to about 6 Mt/y of biomass.

Japan continues its R&D programme on clean coal technologies and aims to establish and introduce the next generation of coal-fired power technologies, such as AUSC (700°C) and IGCC within 10 years. Other technologies such as AUSC (800°C) and IGFC are planned to be introduced in 2030 (Fujii, nd). CCS technology, particularly oxyfuel combustion is expected to be commercially deployed in 2020 (Makino, 2016b).

5.5 Summary

The Japanese coal fleet is modern, relatively young and has the highest average efficiency of (41.6% (LHV, net)) in the world. As Japan is a leader in clean coal technologies, so the majority of its fleet are HELE plants. Japanese coal-fired plants set a benchmark on many levels.

Japan plans to build more coal fired power plants, using the most efficient clean coal technologies. It also advocates HELE technologies around the world, so that access to energy and a secure supply can be ensured in developing countries. As frequently stated by government officials, Japan plans to contribute to the global CO_2 reduction emissions by the dissemination of its technologies and giving financial support to overseas projects. Thus Japan 'will make utmost efforts to maintain the international circumstances for continuing utilisation of coal, while contributing to the reduction of the global greenhouse gas emissions' (Fujii, nd).

6 USA

The USA is the second largest producer and consumer of energy in the world (Nalbandian-Sugden, 2015). In 2015, the country generated about 4 trillion kWh of electricity. Around 67% of this came from fossil fuels, including 33% from coal (EIA, 2016a). The USA coal fleet is dominated by relatively old subcritical and early supercritical units, hence the average efficiency is around 37.4% (LHV, net). However, the country leads the way in pollution emission control standards, especially for mercury, and mercury-specific control technologies. There are also active CCS programmes including work on oxycombustion and chemical looping combustion and research on other advanced clean coal technologies such as AUSC and coal hybrid systems.

6.1 Profile of existing coal fleet

The profile of the American fleet, abstracted from Platts database, is shown in Figures 20 and 21 as well as in Tables 14–15. Currently, there are 402 units of 300 MW or greater capacity. They have a total capacity of 245,794 MW, which represents around 80% of the USA coal capacity (as of March 2016). The majority of the fleet, 63%, are subcritical units (284). Over 90% of these were built before 1990. There are 117 supercritical units with a total capacity of 90,272 MW and only one 665 MW ultrasupercritical unit. Around half of the plants are over 40-years old, making it a relatively old fleet (EPA, 2016). However, almost half (48.5%) are relatively large units, at 600 MW capacity or more.

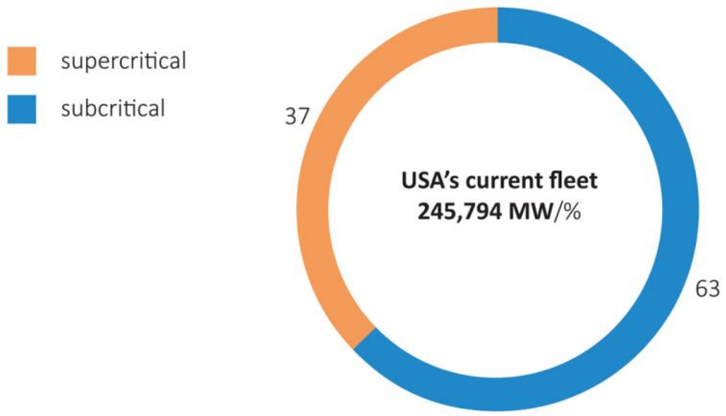

Figure 20 Operating coal-fired fleet in the USA

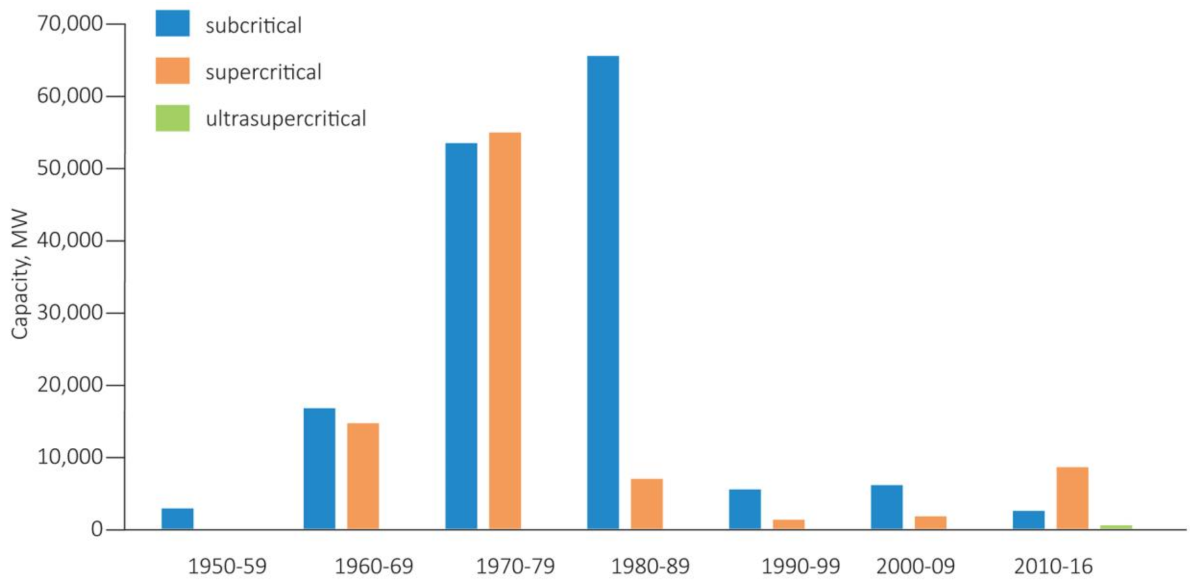

Figure 21 USA's coal-fired fleet, by age

Table 14   Subcritical coal-fired fleet in the USA

Year of commissioning	Unit number	Size range (MW)	Total capacity of the group (MW)	Subcritical capacity (%)	Percentage of total capacity (%)
1950-59	10	300–360	3290.1	2.1	1.3
1960-69	37	310–704	17235.3	11.1	7.0
1970-79	101	300–892	53477.4	34.5	21.8
1980-89	107	315–900	65901.5	42.6	26.8
1990-99	11	330–705.5	5738.5	3.7	2.3
2000-09	13	300–738	6297.8	4.1	2.6
2010-16	5	306–800.3	2916.5	1.9	1.2
Total	284		154857.0	100.0	63.0

Table 15   Supercritical coal-fired fleet in the USA

Year of commissioning	Unit number	Size range (MW)	Total capacity of the group (MW)	Supercritical capacity (%)	Percentage of total capacity (%)
1960-69	25	346–950	15102	16.7	6.1
1970-79	69	386–1320	54991	60.9	22.4
1980-89	8	455–1305	7236	8.02	2.94
1990-99	1	1426	1426	1.6	0.6
2000-09	3	595–890	2355	2.6	1.0
2010-16	11	677–925	9162.4	10.1	3.7
Total	117		90272	100.0	36.7

Figure 22 shows the 665 MW John W Turk Jr plant in Arkansas, which is the only ultrasupercritical plant in the USA. The owner, SWEPCO, had to overcome many regulatory barriers in order to build the plant. As reported by Peltier (2013): 'shortly after SWEPCO announced the project, it then became a target of a national anti-coal campaign and of organised opposition from local groups with land holdings near the plant. Virtually every regulatory and environmental permitting decision was challenged, first in the regulatory process and then in the judicial system'. In December 2011, after nearly four years of litigation, a key settlement was reached. This required that SEPCO, among other things, 'reiterate its decision to phase out a 528 MW coal-fired unit in Texas, build or secure 400 MW of renewable power, and not build any new additional generating units at the Turk site (and within a 30-mile radius)'. Further, SWEPCO agreed to contribute $10 million to support land conservation and clean energy in Arkansas, as well as paying $2 million in attorney fee reimbursements to environmental groups. It was also agreed that the plant would burn only low-sulphur subbituminous coal from Powder River Basin in Wyoming or other subbituminous coal with similar low-sulphur characteristics (Peltier, 2013).

Figure 22 John W Turk Jr plant, Arkansas, USA (Peltier, 2013)

The plant has been in operation since December 2012 and achieves an efficiency of around 42% (LHV, net). It operates with steam cycle conditions of 600°C (main) and 607°C (reheat) temperature and pressure of 26.2 MPa (Santoianni, 2015; Platts, 2016). The unit is equipped with: an SCR system; low-NOx burners with close-coupled over fire air for control of NOx; a dry FGD system and pulsejet fabric filter for SO_2 and PM control; as well as activated carbon injection to reduce mercury emissions (SWEPCO, 2013).

The USA has a long history of addressing air pollution. Since the 1960s, a number of standards have been introduced which apply to coal-fired plants (*see* Section 6.3.1) (IEA, 2016b). Currently, coal-fired power plants must control not only major pollutants such as NOx, SOx and PM but also, mercury and other metals and HCl and HF.

According to Hay (2011) in 2011, 60% of the US coal fleet either had scrubbers (FGD) installed or under construction, 35% had fabric filters, 70% had ESP and around 50% had some form of advanced NOx control (SCR or SNCR). Since then, mercury-specific standards have been introduced. As a significant proportion of mercury can be co-removed by devices for SOx, NOx and PM control, the number of such installations has increased (EIA, 2016d).

In terms of PM pollution control, data from Platts shows that all 402 units have control systems in place. Cold-side electrostatic precipitators are the most common as they are installed on 58% of units. Around 25% of the fleet has fabric filters and 8.2% have hot-side ESP. This varies from data reported by Hay (2011), which is because in this report only plants of 300 MW capacity or more were analysed, whereas Hay reported on the equipment installed on the all power plants. The remaining units have other types of systems, such as wet ESP or a combination of systems including baghouse with different ESP.

According to Platts all analysed units control SOx emissions. The majority of plants (over 61%) use wet limestone scrubbers. This is not dissimilar to the EPA Power Sector Modeling Platform v.5.15 database (2016) which identifies 64% of plants as having a wet scrubber installed and 16% having a dry scrubber. However, it is difficult to say with certainty what type of scrubbers are installed as information on the reagent used is not always provided. Slightly over 24% of units use compliance fuel, with a low sulphur content and one unit is reported to use coal washing.

In terms of NOx reduction, SCR systems alone (31.6% of the units) or in combination with low-NOx burners (14.7% of units) are the dominant technologies. SNCR alone and in combination with LNB is installed on 6.5% units. There is no information on control for more than one fifth of the fleet. The remaining share uses LNB alone (10%) or in combination with OFA and SOFA. There are tens of units using combustion optimisation systems, such as those offered by GE Power Digital Solutions. This technology reduces NOx emissions by real-time optimisation of fuel and air mixing by using neural networks to manipulate relevant fuel and air injection points and It can also control carbon monoxide (CO) (Lockwood, 2015). However, the exact number of units in operation is unclear.

Since 16 April 2015, unless granted an extension, coal-fired power plants larger than 25 MW have to comply with the Mercury and Air Toxics Standards (MATS) (*see* Section 6.3.1). Under this rule, existing coal plants have to remove 80–85% of mercury, depending on the type of coal they fire., while new units, have to achieve around 95% reduction of mercury emissions (Sloss, 2015). The vast majority of plants limit emissions of mercury either by direct control, as a co-benefit of non-mercury specific technologies (SCR, FGD and PM control systems), or by changes in fuel usage (Hutson, 2016). As MATS is a new rule, some plants are still developing their control strategies. Those which have chosen to comply by changing fuel may need to adapt their strategy, as changes in the fuel used, to low mercury and low-sulphur coal is unlikely to be a long-term option (Sloss, 2015). Additionally, the level of mercury removed by co-benefit may not always be sufficient. Hence a number of plants employ mercury specific control methods. Among these, activated carbon injection (ACI) is reported to be the dominant technology as over 140 GW capacity have such systems installed (EIA, 2016d). Several plants have added multiple systems for mercury removal (EIA, 2016d). In recent years, mercury specific technologies have been rapidly developed and demonstrated in the USA. Some of these are still in the demonstration phase. Mercury specific, as well as multipollutant systems able to remove mercury, are described in detail in other IEA CCC reports by Sloss (2012, 2015). The new regulation has helped the USA to become a leader in a mercury specific control technologies. MATS also requires power plants to control non-mercury metals, such as arsenic, and the acid gases HCl and HF. The majority of plants will be able to remove these pollutants with existing control technologies, such as ESP, fabric filters and scrubbers for SOx.

There are also two IGCC power plants in the USA: Polk County and Wabash. While designed for coal, they have been firing pet coke and Wabash is currently being converted in a syngas plant for fertiliser and chemicals production (Smouse, 2016).

6.2 Coal fleet under construction and planned

Currently, there are no coal-fired plants being planned or constructed in the USA and it is unlikely that any coal capacity will be added in the near future (until at least 2025). This is due to many reasons, including the low price of natural gas as well as tax credits for renewable energy generation, especially wind and solar. Consequently, the retirement of coal-fired generating capacity is expected. The EIA, in its Annual Energy Outlook 2016, predicts a coal capacity retirement of between 24–28% from 2015 to 2030. This corresponds to up to 70 GW. This estimate depends on various scenarios, such as implementation of the Clean Power Plan and how the regions choose to comply with the CO_2 emission standards (mass-based or rate-based targets) (EIA, 2016c). Although, no additional capacity is planned, the number of R&D programmes on advanced technologies suggest that it is possible that in the longer term some of the old plants may be replaced by new, more efficient units.

6.3 Research and development

Despite not building new pulverised coal-fired plants, the US Department of Energy's (DOE) R&D programmes show a commitment to developing and implementing new technologies. For example, there are five major CCS demonstration projects co-funded by the US DOE, three of which are for coal-fired plants. One of them is the Petra Nova Carbon Capture and Sequestration Project Construction project. Located in Texas, Petra Nova is a post-combustion CO_2 capture project with a total cost of approximately $1 billion; $167 million of the total was provided by the US DOE. The project aims to demonstrate the ability of an advanced amine-based CO_2 capture system to capture 90% of the CO_2 emitted from a flue gas slipstream equivalent to 240 MW in size. The host power generation unit is not expected to be derated because the power and thermal energy required to operate the CO_2 capture and compression system will be provided by a natural gas-fired cogeneration plant comprised of a gas turbine with a heat recovery boiler. The captured CO_2 will be compressed and transported through an 80-mile (129 km) pipeline to an operating oil field where it will be used for enhanced oil recovery (EOR) and ultimately stored. The project is scheduled to start operation later in 2016 (McMahon, 2016). Other CCS projects, in various stages of development, include advanced IGCC with CCS. They are:

- Summit TX Clean Energy Project, starting in late 2018, carbon capture will be used for EOR; and
- Kemper County IGCC Project, starting in January 2017, CO_2 captured will be used for EOR.

Southern Company's Kemper County IGCC Project is currently the only CCS IGCC power plant that is under construction (Power Magazine, 2016). The plant, originally projected to be placed into service in May 2014, has faced a number of delays and cost overruns. Mississippi Power put the combined cycle and other common facilities online by August 2014, but has experienced difficulty placing the gasifiers in operation. Currently, the start of commercial operation is predicted to be sometime in January 2017 (Power Engineering, 2016). The plant will produce syngas using local Mississippi low rank coal. It will convert 12,000 tons of lignite per day to produce 582 MW (net) of electricity (NETL, nd). The plant will utilise KBR's TRIG™ gasifier technology, which has been developed by KBR and Southern Company in conjunction with DOE at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama. Initial production of syngas from the first gasifier at the plant began in July 2016, and from the second gasifier in September 2016 (Power Magazine, 2016b; PRNewswire, 2016). The plant is also designed to capture at least 65% of CO_2 from the syngas. The carbon dioxide will be sold for EOR.

Additionally, the National Energy Technology Laboratory (NETL) is working on the potential to reduce emissions from coal-fired power plants by integrating other power generation systems with advanced steam cycles. The focus of the work is on creating hybrid coal and renewable systems, but a hybrid system integrating a coal plant and a natural gas-fired fuel cell was also evaluated. The screening analysis found that integrating solar feed water heating systems with a coal power plant shows promise for near term compliance with the US New Source Performance Standards (NSPS) for GHG emissions from coal plants. These systems have been demonstrated at a small scale in the USA and use commercially available solar-thermal Rankine cycle power plant components. The systems, which include the use of molten salt thermal storage, appear to be cost-competitive even in areas with low levels of annual direct radiation, particularly when advanced steam cycles are used. Additionally, the integration of wind generation with coal also shows promise, but if electricity storage is required the economics may be more challenging. It was found that solar photovoltaics (PV) were less suitable than solar thermal integration at current or projected PV technology levels. This is because PV was less economic than solar thermal, and it also relied on batteries which are costly and may have reduced cycle lifetimes (Tarka, 2016). Thermally integrating fuel cells with coal might show promise in the future. However, there are several challenges such as: the high cost; small size (2.8 MW) compared to most coal plants, meaning that many units are required; uncertainty regarding reliability and maintenance costs, and the fact that they are not currently optimised to output the right temperature water splits for integrating into the coal feed water heating system. All of these make integrating fuel cells with coal a longer-term option for NSPS compliance (Tarka and others, 2016a).

NETL is also working on the potential of coal-to-liquids (CTL) and coal- and biomass-to-liquids (CBTL) as near-term options for CCS deployment. While these systems are not economically competitive at the current price of oil, they do have a low incremental cost of CO_2 capture (19 $/t) as the CO_2 is already being separated as part of the liquid fuel production process. According to Tarka and others (2016b) a number of factors might make CCS-equipped CTL and CBTL systems more deployable. The primary one is that CBTL with CCS enables the large-scale production of low-carbon transportation fuels. It seems that few, if any, other opportunities exist to produce such low-carbon fuels, which creates both a market premium and a 'Now Term' pathway for governments or entities interested in deploying these systems rapidly. Other benefits include the ability to leverage varying amounts of biomass depending on its availability, while having a secure energy feedstock (coal) as a backup, and that early mover CTL/CBTL systems could help drive down the price of IGCC systems through deployment, given that they produce a higher value product (fuels are higher value than electricity) (Tarka and others, 2016b).

The US DOE and the Ohio Coal Development Office have sponsored a Materials Program for advanced ultrasupercritical (AUSC) steam power generation. The Program started in 2000 and aims to identify, evaluate, and qualify the materials needed for the construction of the critical components (boiler and turbine) of coal-fired power plants capable of operating at much higher conditions than those of current ultrasupercritical plants. Research is focused on nickel-based alloys with the aim of operating at much higher temperatures than other international programmes (760°C compared to 700°C). The Program takes into account conditions particular to the USA. For example, the materials need to be corrosion resistant for all American coals, even high-sulphur Ohio coal. Various tests have been performed so far. These include the world's first steam loop operating at 760°C for 33 months, with more than 16,000 operating hours. Evaluation showed little to no wastage of material. A report on the work can be found at: http://www.osti.gov/scitech/biblio/1243058. The Materials Program aims to have a demonstration plant of 350 to 600 MW operational by 2025 (Purgent and Hach, 2016).

The US DOE Office of Fossil Energy's Strategic Center for Coal supports R&D of supercritical CO_2 power cycles (Brayton cycle). So far, a number of R&D projects have been awarded funding from the DOE. Most recently, up to $80 million has been announced for a six-year project to design, build, and operate a 10 MW supercritical carbon dioxide (sCO_2) pilot plant test facility in San Antonio, TX. This project will be managed by a team led by the Gas Technology Institute (GTI), Southwest Research Institute® (SwRI®), and General Electric Global Research (GE-GR). If successful, this facility has a potential to achieve steam cycle efficiency of over 50%. Such a cycle could provide significant efficiency gains in geothermal, coal, nuclear, and solar thermal power production. According to the US DOE, currently no commercially feasible sCO_2 facility exists for high temperature and high efficiency system testing. Hence, this project is 'an opportunity for industry and government to work together to develop and mature the sCO_2 power cycles at the pilot-scale, bringing it one step closer to commercialisation' (Energy.gov, 2016). More information can be found at: http://energy.gov/under-secretary-science-and-energy/articles/doe-announces-80-million-investment-build-supercritical.

The US DOE is also working on oxycombustion and chemical looping combustion as these are seen as technologies with the potential to drive down the cost of electricity of coal plant with CCS. Currently these projects are at laboratory and pilot scale, but the DOE aims to develop large-scale pilot validation by 2025 and gather the data necessary for demonstration by 2030 (Smouse, 2015).

6.4 Drivers and barriers for implementation of advanced clean coal technologies

Until recently, coal has been a dominant fuel for power plants. However, as noted by Nalbandian-Sugden (2015) the coal industry in the USA is facing unprecedented challenges. This is largely due to the growing production of shale gas, falling prices of renewables and various environmental regulations (Nalbandian-Sugden, 2015a; BP, 2016).

In the case of pollution control systems for NOx, SOx, PM and most recently mercury and other air toxics, regulation has been a clear driver for installations. Figure 23 shows changes in coal capacity and pollution control equipment as a result of the Mercury and Air Toxics Standards. Data is provided for the period December 2014 to April 2016. The vast majority of power plants have been ready to comply with MATS by co-benefit removal of regulated pollutants (mercury, non-Hg metals and acid gases) in the NOx, SO_2 and PM control systems. About 87 GW of coal-fired plants installed pollution control equipment and almost 20 GW of coal capacity retired. Over one-quarter of the retirements occurred in April 2015, which was the initial compliance date for the MATS rule (EIA, 2016d). As reported by the EIA (2016d), a few plants, totalling 2.3 GW capacity, received additional one-year extensions, giving them until April 2017 to comply, while approximately 5.6 GW of coal capacity switched fuel, primarily to natural gas.

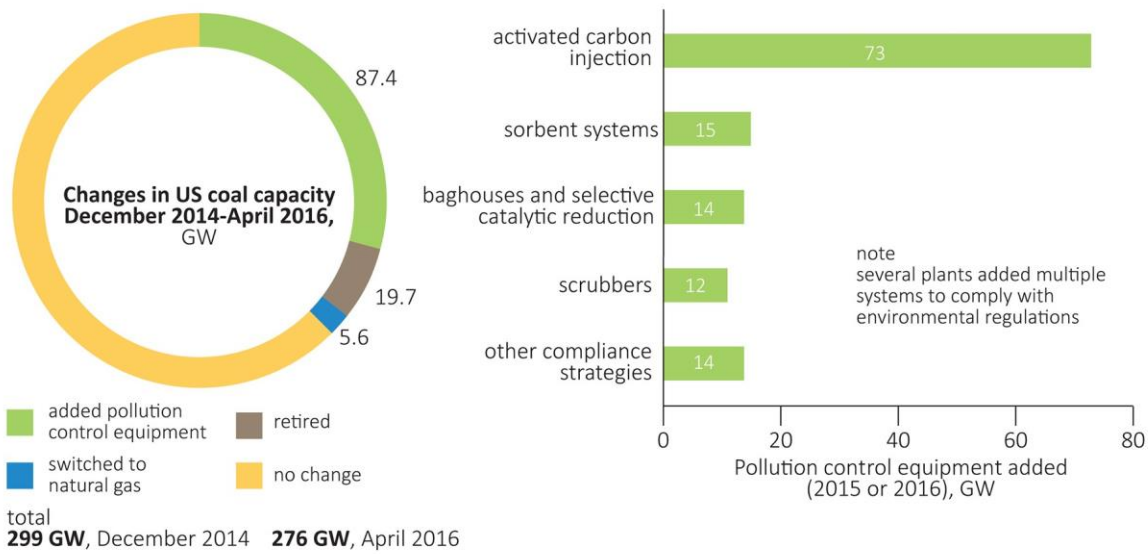

Figure 23 Changes in US coal capacity, December 2014 to April 2016 and pollution control equipment added in 2015 and 2016 (EIA, 2016d)

Pollution control equipment was added to 87.4 GW of coal capacity to comply with MATS. The main technology fitted was activated carbon injection systems (ACI) which were installed on more than 73 GW of coal-fired capacity in 2015 and 2016.

EIA (2016d) reports that other MATS compliance strategies included the modification of existing emissions control equipment, the addition of new systems or capabilities, or some combination of operational changes and new investments to improve mercury capture or to achieve other environmental control objectives, such as reducing emissions of PM or NOx. Many units may have installed more than one type of control system. EIA (2016d) estimates that operators invested at least $6.1 billion from 2014 to 2016 to comply with MATS and other environmental regulations.

Another piece of legislation which, if implemented, will have a great impact on coal-fired power plants is the Clean Power Plan (CPP). The US EPA estimates that the CPP would reduce CO_2 emissions from the power sector by 32% from 2005 levels by 2030 (EIA, 2016c). The CPP gives some flexibility to states in terms of how the CO_2 reduction can be achieved. This includes: switching from carbon-intensive fuels such as coal to less carbon-intensive natural gas-fired power plants or to zero-carbon technologies (such as renewables and nuclear power). Other options include improving plant efficiency to reduce fuel use and increasing energy efficiency to reduce energy demand. As noted by the EIA (2016c), compliance choices made by the states, as well as any future court decision regarding the rule, would have implications for plant retirements, capacity additions, generation by fuel type, demand, and prices (EIA, 2016c). It is worth noting that, prior to COP21, the USA pledged 26–28% domestic reduction in greenhouse gas emissions by 2025 compared to 2005. This includes the land sector and currently excludes international credits (Carbon Brief, 2015).

Natural gas combustion generally produces about half the greenhouse gas emissions of coal, as well as lower emission levels of gaseous pollutants, so substituting coal with natural gas has been seen as beneficial. However, as noted by Nalbandian-Sugden (2015b), studies show that fugitive methane emissions from gas exploration, extraction, transmission and distribution make the benefits of such substitution, questionable, especially so in the short term (10–20 years). This is because methane is a more potent greenhouse gas than carbon dioxide. Realising this, the EPA has recently announced comprehensive steps to address methane emissions from both new and existing sources in the oil and gas sector. For new, modified and reconstructed sources, a set of standards that will reduce methane, volatile organic compounds (VOCs) and toxic air emissions in the oil and natural gas industry is being finalised. The EPA has also started the process of controlling emissions from existing sources by issuing an Information Collection Request (ICR) for public comment that requires companies to provide the information that will be necessary for the EPA to reduce methane emissions from existing oil and gas sources (EPA, 2016a). This action could potentially impact the number of future oil and gas-fired plants, and thus the number of coal-fired plants switching to natural gas could be lower than if the methane emissions were left unregulated.

Although coal use is declining in the USA, it is still predicted to have a significant place in the future energy mix – 21% in 2030 and 18% in 2040. Further, the US DOE is undertaking and supporting many R&D and demonstration programmes on AUSC, CCS and hybrid coal and renewable systems, among others, which suggests a future for coal in the USA. Projects on advanced fossil fuel technologies can be awarded DOE's grants for R&D and pilot demonstration. Funding for initial commercial development can be obtained from the DOE Loan Guaranty Office in the form of loan guarantees (Schneir and Neary, 2016). As of October 2015, $8.5 billion was made available for projects on advanced fossil energy, that included carbon capture and low carbon power systems. Additionally, there are a number of incentives to facilitate carbon capture, utilisation and storage (CCUS) such as tax credits. The US DOE (2016) reports that the following tax and financial incentives to support CCUS deployment are currently under consideration by policy makers and stakeholders and include:

- Incentives for CO_2-EOR, including expansion and/or modification of existing Section 45Q provisions, (tax credits on a per-ton basis for CO_2 that is sequestered).
- CO_2 price stabilisation, which aims to provide long-term financial certainty for CO_2 prices.
- Master Limited Partnerships (MLP), which provide the tax benefits of a limited partnership to qualified projects.
- Private Activity Bonds (PAB), which expand access to capital and reduce the cost of borrowing for qualified projects.
- Investment tax credits (ITC), which provide a tax credit for the installation of capture equipment and in some cases, supporting infrastructure.

Some of the barriers to new coal-fired plants in the USA are reported by Peltier (2013), who noted that commissioning of the J Turk Jr plant, the only USC plant in the USA, 'culminated almost seven years of legal, regulatory, and construction work to bring the $1.8 billion project – the most expensive project ever built in the state of Arkansas – to completion'.

6.4.1 Overview of policy and regulatory framework

The Clean Air Act

The Clean Air Act (CAA) of 1963 and its 1977 and 1990 amendments form the basis for air pollution control regulation in the United States, authorising the development of federal and state regulations to limit emissions from industrial sources and transportation (IEA CCC, 2015c; IEA 2016b). The CAA has three main components: ambient air quality standards, emission standards and permitting requirements.

The ambient levels for six common pollutants, including NOx, SO_2 and PM (with PM_{10} and $PM_{2.5}$ regulated separately) are set in National Ambient Air Quality Standards (NAAQS), whereas emission limits for new industrial sources of pollutants, such as coal-fired power plants, are set in New Source Performance Standards (NSPS). NSPS apply to utility coal plants over 73 MW heat input (including IGCC from March 2005). For SO_2, limits are: 160 and 640 mg/m^3 for existing plants built 1997-2005 and 1978-1996, respectively, and 160 mg/m^3 for new plants. Limits for NOx depend on the age of power plants. For the existing power plants, they are: 117 mg/m^3 (built after 2005), 160 mg/m^3 (1997-2005) and 640 mg/m^3 (1978-1996). The PM limits are: 23 mg/m^3 for new and existing plants. There are some exceptions, for example, for plants firing 100% anthracite or solid-solvent refined coal. The details of these can be found in the IEA CCC emission standards database: http://www.iea-coal.org.uk/documents/82575/9515/United%20States%20of%20America. The NSPS do not dictate the particular technologies to be used, but they are established based on what the US EPA defines as the 'best system of emission reduction' and they also take cost into account (IEA, 2016b). The CAA also requires that all major new and modified stationary pollutant sources, including coal-fired power plants obtain pre-construction permits under the New Source Review programme.

The Acid Rain Program

A major amendment to the CAA in 1990 (*see* http://www2.epa.gov/clean-air-act-overview/clean-airact-text) introduced the Acid Rain Program (ARP). This is aimed to reduce SO_2 and NOx emissions considerably from existing emitters through a cap-and-trade system. The first phase of the programme ran from 1995 to 1999 and was applied to 110 major sources which were allocated emissions allowances based on an emission rate of 2.5 lb/million Btu (3.96 g/GWh) of SO_2 and a plant's average fuel consumption in the base year. It aimed to achieve an annual cap of 8.95 Mt/y. A second phase from 2000 expanded the programme to all fossil-fuel fired boilers over 75 MWe and based allowances on 1.2 lb/million Btu (1.9 g/GWh) of SO_2. NOx emissions were limited to 0.45 lb/million Btu (0.71 g/GWh) for tangentially-fired coal boilers, and 0.46 lb/million Btu (073 g/GWh) for wall-fired boilers (IEA CCC, 2015c).

Interstate emissions

The Clean Air Interstate Rule (CAIR), a variant on the cap-and-trade system, was introduced in 2005, in response to the fact that emissions can also contribute to NAAQS violations in states downwind of the emitting source. The rule lowered the SO_2 cap on 27 states and the District of Columbia by 70% by requiring three SO_2 allowances in the place of one. Although finally implemented in 2008, legal proceedings by states and utilities against this rule have led the EPA to propose the Cross-State Air Pollution Rule (CSAPR) as its replacement (*see* http://www3.epa.gov/airtransport/CSAPR/index.html). The CSAPR will essentially replace the existing ARP allowances with four separate cap-and-trade programmes covering annual SO_2 and NOx emissions, and summertime NOx emissions which contribute to ozone formation. The 27 states addressed in the CAIR will also be split into two groups with different caps, both of which are more stringent than under the CAIR. After facing a number of legal challenges, the latest US Court of Appeal for the DC Circuit decision (July 2015) has kept the CSAPR in place (IEA CCC, 2015c).

Mercury and air toxics emissions

The USA introduced the world's first mercury standards for power plants. Although the first standards, under what is known as the Clean Air Mercury Rule (CAMR) have been annulled, due to a legal decision that the EPA's regulation was inconsistent with the requirements of Clean Air Act, the second rule by the EPA, the Mercury and Air Toxic Standard, known as MATS, has been implemented. The standard applies to new and existing power plants over 25 MW and covers emissions of mercury, other heavy metals, as well as the acid gases HCl and HF. Under the proposed rule, filterable particulate matter (PM) can be used as a surrogate for the total emissions of non-mercury toxic metals, and SO_2 can be a surrogate for both acid gases, while mercury must be measured separately. Existing plants are provided with limits based on both fuel input and energy output, whereas new plants must adhere to output-based limits only. The rule differentiates between' low rank virgin coal' (lignite) and 'not low rank virgin coal'. Since 16 April 2016, all existing plants have to meet emission limits for mercury. For example, for not low rank coal output-based standard is 4.0E-2 lb/GWh (18.1 g/GWh), while for low rank coal it is 1.3E-2 lb/GWh (5.9 g/GWh). Currently, the USA's mercury standards are the strictest in the world. Detailed information on MATS can be found at: https://www.gpo.gov/fdsys/pkg/FR-2012-02-16/pdf/2012-806.pdf.

Clean Power Plan

The Clean Power Plan, promulgated in October 2015, aims to cut CO_2 emissions from existing emitters. The target is a 30% reduction in national CO_2 emissions by 2030 from the 2005 level. Under this legislation, states would be given specific CO_2 goals and guidelines for the development of emission reduction plans which can be based on a range of possible strategies, including energy efficiency improvements, investment in renewables, and power plant upgrading. It is left up to the states to develop their own plans to meet their specific CO_2 goal. Under the CPP rule, states would be able to choose either mass-based or rate-based emissions targets. A mass-based target specifies an annual limit of CO_2 that can be emitted by states from the affected sources. A rate-based target requires states to meet an annual adjusted emission rate measured in lbs CO_2/MWh. This is based on emissions from affected sources divided by generation from affected sources, which for this calculation includes new non-emitting sources, such as nuclear and renewable capacity, and incremental energy efficiency. The rule also affords flexibility in other areas, such as regional cooperation through trading (EIA, 2016c). More information can be found on the EPA website (http://www2.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants) and the final rule is available at: https://www.federalregister.gov/articles/2015/10/23/2015-22837/standards-of-performance-for-greenhouse-gas-emissions-from-new-modified-andreconstructed-stationary#h-8

6.4.2 Future trends

In general, coal use in the US power sector is expected to decline further. Nevertheless, the EIA in its Annual Energy Outlook (2016) predicts that coal will still have a significant share in the future US energy mix – around 21% in 2030 and 18% in 2040. There are many factors which will impact on the future of coal-fired plants, including whether or not the Clean Power Plan is implemented, or other regulation introduced such as standards to cut methane emissions from oil- and gas-fired plants, and setting of a climate change target. There are some uncertainties too, including the rate of GDP growth, the pace of transition to a lower-carbon economy as well as the potential for shale gas and oil (BP, 2016).

The EIA (2016c) investigated the impact of implementing the Clean Power Plan, in relation to chosen compliance methods (*see* Section 6.3.1). Five different scenarios were analysed, details of which can be found at: https://www.eia.gov/forecasts/aeo/cpp.cfm. In general, the energy generation capacity is expected to grow, but the coal share to decline. Across different scenarios, coal will have a reduced share in the energy mix by between 24–28% from 2015 to 2030 (*see* Figure 24). The decline from 2015 to 2040 varies among the cases, ranging from 20% to 32% across the cases that keep the CPP target constant after 2030. The rate-based case (when states meet an annual adjusted emission rate) allows some increase in coal generation in the later years, assuming sufficient renewable generation is available to offset it. In the mass-based case, coal generation continues to be reduced and lower-emitting sources are used to meet new demand and maintain the same emissions cap. In the CPP Extended case, which assumes that the CO_2 emissions target continues to decline after 2030, coal generation in 2040 is 52% below 2015 levels. In the No CPP case, coal electricity generation increases slightly from 2015 levels, due to an increase in natural gas prices and as existing coal units run at higher capacity factors than in 2015, but remains relatively flat after 2020. Most growth in electricity demand is met by natural gas-fired plants and renewable capacity, which are more economic to build to meet new demand even without the CPP in place.

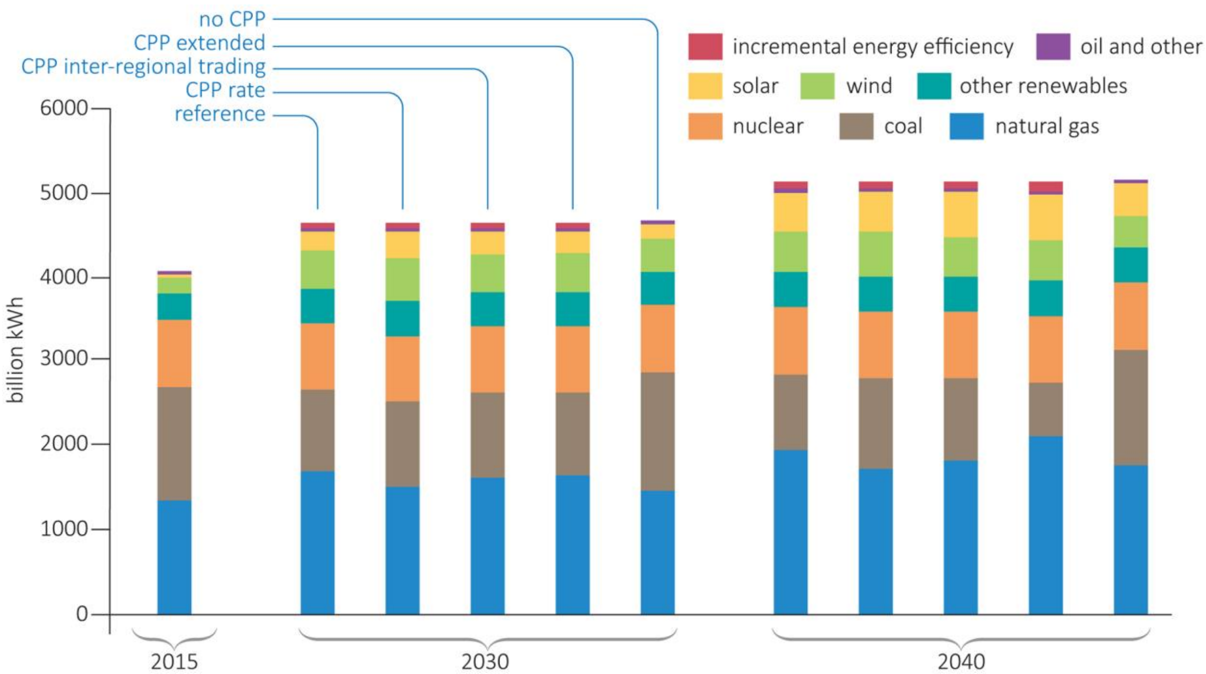

Figure 24 USA – electricity generation by fuel type in five cases, 2015, 2030 and 2040 (EIA, 2016c)

Additionally, according to the EIA (2016e), in 2017, the rising cost of natural gas may encourage more coal-fired generation. This means that coal's share in the energy mix could increase from 30.3% to 31.1% and natural gas generation could fall from 34.3% to 33.3%. With no new coal-fired capacity added, the existing coal-fired-plants would be required to run more hours.

6.5 Summary

The American coal-fleet is dominated by relatively old subcritical and supercritical units, hence the average efficiency is around 37.4% (LHV, net). Almost half the units are 600 MW or larger. There is only one ultrasupercritical unit.

There are no new pulverised coal fired power plants being planned or built. However, there are four CCS projects in various stages as well as R&D projects on AUSC, hybrid coal and renewable systems, and oxycombustion and chemical looping combustion. As coal is still predicted to have a significant place in the future energy mix it is possible that once new technologies are demonstrated (after 2025), old coal-fired units may be replaced with new systems. The R&D work also means that the USA will have developed clean coal technologies available for export.

The USA leads the way in air emission standards for toxics, especially mercury. Consequently, the USA has become the leader of mercury-specific control technologies.

In terms of air pollution control technologies for NOx, SOx, PM and mercury – legislation has been a clear driver for implementation of advanced air pollution control technologies. On the other hand, the low price of natural gas and the decreasing cost of renewables as well as proposed legislation such as the Clean Power Plan are barriers for building new coal-fired plant.

7 Conclusions

There is ongoing international debate on the role of coal in the future energy mix. There are vast differences in governments' attitudes towards coal and reducing emissions from its combustion, which are reflected in the variations in the deployment of clean coal technologies and coal-fired power generation units around the world.

China, Japan, the EU and USA have the strictest emission limits for coal-fired power plants (IEA, 2016b). They are frequently used as reference values in national and international debates on the redefinition of threshold values for coal-fired power stations. Hence, data from these regions are of particular interest, especially now as countries develop strategies to meet COP21 climate targets. This report provides a snapshot of the coal fleet for these important regions, their most efficient coal-fired plant, the pollutant control technologies they use, the legislation and other drivers and barriers that influence the development and introduction of new clean coal technologies and units.

China

The Chinese energy sector has undergone a huge transformation in recent years. The coal-fired fleet has an average operational efficiency of 38.6% (LHV), which exceeds the average across coal-fired plants in the IEA member countries (IEA, 2016a). Once an importer of coal technologies, now China is an exporter of advanced technologies and continues to invest in R&D. For example, the double-reheat 1000 MW USC Guodian Taizhou II unit 3, which was domestically designed, manufactured and built, and has been in operation since September 2015, has reached an efficiency of 47.82% (net, LHV), the highest both in China and in the world for a double-reheat coal-fired power plant. Its emissions are low: PM – 2.3 mg/m^3, SO_2 – 15 mg/m^3 and NOx – 31 mg/m^3 (Zhu, 2016).

Every Chinese power plant is equipped with PM and sulphur control equipment, and almost all plants have nitrogen oxide removal devices (Wang, 2016). Coal-fired plants in priority regions have pollutant emissions as low as those of gas-fired power plants. Moreover, all coal-fired plants will have to be ultra-low emission by 2020 (Zhu, 2016).

Strong policies, tight environmental and performance standards and their rapid implementation, combined with available finance for coal-fired projects as well as feed-in tariffs for energy generated from ultra-low emission power plants are the main drivers for the implementation of advanced clean coal technologies in China.

Overcapacity, and in some areas, competition for limited water resources as well as the rapid development of renewable energy resources which can reduce the profitability of coal-fired power plants are the main barriers to building new coal-fired plants, even state-of-the-art ones.

EU

Coal-fired power generation across the EU varies greatly. While the EU works towards Energy Union and tightens its environmental regulations for coal-fired power plants, some countries, such as the UK and Germany, have pledged to reduce or phase out coal-fired power plants. However, despite, ambitious EU targets to mitigate climate change, some states, particularly Poland, will continue to rely on coal. A few new coal-fired plants are being planned and built.

Although, the average coal-fired power plant efficiency is 38 % (LHV, net) (VGB, 2012) and a significant proportion of the fleet is relatively old, the EU is also home to one of the most advanced coal-fired plants, the 1100 MW USC Maasvlakte Power Plant 3 in Netherlands. This plant achieves efficiency of 47% (net, LHV), can cofire up to 30% biomass, is carbon capture ready and can supply district heat (Blankenspoor, 2015). Its average emission levels are: SO_2 – 5-25 mg/m^3, NOx – 60-65 gm/m^3 and PM – 1–2 mg/m^3 (Nederveen, 2016). The plan is for this unit to take part in the Dutch CCS pilot project, which if combined with cofiring biomass will enable the plant to achieve CO_2 emission levels as low as those of a gas-fired power plant (Energy Hub West, 2016; Nederveen, 2016).

As the EU has strict emission standards, pollution control systems for NOx, SO_2 and PM are widely deployed. The EU has ambitious targets to reduce greenhouse gas emissions by 40% by 2030 and by 80-95% by 2050 compared to 1990 levels. To meet these targets would require all coal-fired power plants wishing to operate after 2030 to have CCS in place. However, despite the availability of significant funds from the European Commission, work on CCS has stalled in the EU. The carbon price under the ETS currently is too low to encourage industry to invest. This is obviously a significant barrier to building new coal-fired plants. Yet, this may change, and a revival of R&D and funding for CCS may occur should utilities perceive that investing in CCS may be a cheaper option than abandoning their assets (Reuters, 2016a). On the other hand, significant R&D work on AUSC plant, shows a commitment to the future deployment of advanced clean coal technologies, whether within the EU or further afield.

Japan

The Japanese coal fleet is modern, relatively young and has the highest average efficiency (41.6% LHV, net) in the world. As Japan is a leader in clean coal technologies, the majority of its fleet are HELE plants. Japanese coal-fired plants set a bench mark on many levels. For example, the Isogo coal-fired plant unit 2 has average emissions in single digit-levels for NOx and SO_2 and below 5 mg/m^3 for PM and is considered to be the world's cleanest coal-fired power plant in terms of emissions intensity (Santoianni, 2015).

Japan plans to build more coal-fired power plants and will employ the most efficient clean coal technologies in these units. It also advocates using HELE technologies around the world, so that energy access and a secure supply can be ensured in developing countries. As frequently stated by government officials, Japan will contribute to global CO_2 reduction by dissemination of its technologies and financial support to overseas projects and 'will make utmost efforts to maintain the international circumstances for continuing utilisation of coal, while contributing to the reduction of the global greenhouse gas emissions' (Fujii, nd).

USA

The American coal fleet is dominated by relatively old units, both subcritical and supercritical, hence its average efficiency is around 37.4% (LHV, net). Its most efficient coal-fired unit is the 665 MW John Turk Jr plant in Arkansas. It achieves an efficiency of 42% net (LHV) and is the only ultrasupercritical unit in in the country. At the moment, there are no new coal-fired power plants being planned or built.

In terms of air pollution control technologies for NOx, SOx, PM and mercury – legislation has been a clear driver for the implementation of advanced clean coal technologies. The country leads the way in air emission standards for toxics, especially mercury. Consequently, the USA has become the leader in mercury specific control technologies. US plants also have a high rate of installation of NOx, SOx and PM pollution control systems too. On the other hand, low prices of natural gas and decreasing prices of renewables as well as proposed legislation such as the Clean Power Plan are barriers for building new coal-fired plant.

However, there are CCS projects in various stages as well as R&D projects on AUSC, hybrid coal and renewable systems as well as oxycombustion and chemical looping combustion. As coal is still predicted to have a significant place in the future energy mix (21% in 2030 and 18% in 2040) it is possible that once new technologies are demonstrated (after 2025), old coal-fired units could be replaced with new systems. Additionally, with market for CO_2 to use in EOR and various R&D as well as tax incentives and federal support for carbon capture, utilisation and storage, the USA seems to be currently a leader in both CCUS and CO_2-EOR.

There is uncertainty regarding the future of coal-fired plants across China, the EU, Japan and the USA. The role of coal in their energy mixes is changing, but coal is still predicted to have a significant share in the future. Coal-fired plants continue to become more efficient and less polluting and there is strong R&D ongoing on new technologies such as AUSC, coal and renewable hybrid system and CCS.

8 References

ADB (2014) *Japan, ADB announce fund to promote low-carbon technologies in Asia.* Available at: http://www.adb.org/news/japan-adb-announce-fund-promote-low-carbon-technologies-asia (Jun 2014)

Baruya P (2016) London, UK, IEA CCC, *personal communication* (Aug 2016)

Blankenspoor A (2015) *Maasvlakte power plant 3; theory versus practice*. Available at: http://www.mega-project.eu/assets/exp/resources/Aris_Blankenspoor_MPP3_theory_versus_practice_rev_20150410_sv.pdf (Apr 2015)

BP (2016) Energy Outlook edition 2016. Available at: https://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2016/bp-energy-outlook-2016.pdf (2016)

Caldecott B, Dericks G, Tulloch, D, Kruitwagen L, Kok I (2016) *Stranded assets and thermal coal in Japan – Working paper – May 2016*. Available at: http://www.smithschool.ox.ac.uk/research-programmes/stranded-assets/satc-japan.pdf

Carbon Brief (2015) Paris climate pledge tracker: INDC database. Available at: https://docs.google.com/spreadsheets/d/1LtaBOv70pvXVPDgLUGtTKnSxofjfZy7jx06bTSaMaH4/pubhtml?gid=14385633&single=true (Sep 2015)

Carpenter A (2013) *Advances in multi-pollutant control*. CCC/227, London, UK, IEA Clean Coal Centre, 82 pp (Nov 2013)

Di Ginonfrancesco A, Tizzanini A, Jedamzik M, Stolzenberger C (2014) *ENCIO project: An European approach to 700°C power plant.* Advances in materials technology for fossil power plants: Proceedings from the Seventh International Conference in Walikoloa, Hawaii, 22-25 October, 2013. Available at: https://books.google.co.uk/books?id=ErppBAAAQBAJ&pg=PA10&lpg=PA10&dq=ENCIO+program&source=bl&ots=pGQSJ3ucXs&sig=jg5avaN2qfHgcnPn7HLCQkUki60&hl=en&sa=X&ved=0ahUKEwjAv6H-6ePOAhVJC8AKHWoiDwwQ6AEILDAC#v=onepage&q&f=false (2014)

Dodson S (2014) Japan and Ukraine work together in review of coal-fired power plants. Available at:http://www.worldcoal.com/coal/12082014/Ukraine-and-Japan-in-coal-partnership-1193/ (Aug 2014)

EC (2016a) *The Industrial Emissions Directive. summary of directive 2010/75/EU on industrial emissions (integrated pollution prevention and control).* Available at: http://ec.europa.eu/environment/industry/stationary/ied/legislation.htm

EC (2016b) *Coal and other solid fuels*. Available at: https://ec.europa.eu/energy/en/topics/oil-gas-and-coal/coal-and-other-solid-fuels Accessed on 23 July 2016

EC (2016c) *2050 Energy strategy*. Available at: http://ec.europa.eu/energy/en/topics/energy-strategy/2050-energy-strategy

EIA (2015) *Japan international energy data and analysis.* Available at: https://www.eia.gov/beta/international/analysis.cfm?iso=JPN (Jan 2015)

EIA (2016a) *What is U.S. electricity generation by energy source?* Available at: https://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3 (Apr 2016)

EIA (2016b) *Effects of the clean power plan.* Available at: http://www.eia.gov/forecasts/aeo/section_issues.cfm#cpp (Jul 2016)

EIA (2016c) *Annual Energy Outlook 2016 early release*. Available at: https://www.eia.gov/forecasts/aeo/er/pdf/0383er(2016).pdf (May 2016)

EIA (2016d) *EIA electricity generator data show power industry response to EPA mercury rule*. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=26972 (July 2016)

EIA (2016e) *Energy-related CO_2 emissions from natural gas surpass coal as fuel use patterns change*. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=27552 (Aug 2016)

ENERGY.GOV (2016) *DOE Announces $80 Million Investment to Build Supercritical Carbon Dioxide Pilot Plant Test Facility* Available at: http://energy.gov/under-secretary-science-and-energy/articles/doe-announces-80-million-investment-build-supercritical (Oct 2016)

Energy Hub West (2016) http://www.energyhubwest.nl/energy-hub-west (2016)

EPA (2016a) *EPA releases first-ever standards to cut methane emissions from the oil and gas sector.* Available at: https://www.epa.gov/newsreleases/epa-releases-first-ever-standards-cut-methane-emissions-oil-and-gas-sector (May 2016)

EPA (2016b) *Mercury and Air Toxics Standards (MATS).*
Available at: https://www.epa.gov/mats (webpage actualised at July 2016)

EU Publications Office (2013) *The EU Emissions Trading System* (EU ETS) Available at: http://ec.europa.eu/clima/publications/docs/factsheet_ets_en.pdf (Oct 2013)

Eurelectric (2015) *Power statistics and trends: the five dimensions of the Energy Union*. Available at: http://www.eurelectric.org/media/249736/power-statistics-and-trends-the-five-dimentions-of-the-energy-union-lr-2015-030-0641-01-e.pdf (Dec 2015)

European IPPC Bureau JOINT RESEARCH CENTRE Institute for Prospective Technological Studies Sustainable Production and Consumption Unit (2016) *Best Available Techniques (BAT) Reference Document for Large Combustion Plants.* Available at: http://eippcb.jrc.ec.europa.eu/reference/BR EF/LCP_FinalDraft_06_2016.pdf

European Parliament (2015b) *Briefing: EU position for COP 21 climate change conference*. Available at: http://www.europarl.europa.eu/RegData/etudes/BRIE/2015/572787/EPRS_BRI(2015)572787_EN.pdf Accessed on 23 July 2016

European Parliament (2015a) *Briefing: Biomass for electricity and heating. Opportunities and challenges* Available at: http://www.europarl.europa.eu/RegData/etudes/BRIE/2015/568329/EPRS_BRI(2015)568329_EN.pdf (Sep 2015)

Eurostat (2015) *Energy statistics introduced*. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_statistics_introduced Accessed on 23 July 2016

Eurostat (2016) *Population, EU-28, 1960–2016* http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Population,_EU-28,_1960%E2%80%932016_(%C2%B9)_(at_1_January,_million_persons)_YB16.png Accessed on 24 Nov 2016.

Foreign Policy (2015) *Japan beats on nuclear and coal for future power*. Available at: http://foreignpolicy.com/2015/04/08/japan-bets-on-nuclear-and-coal-for-future-power/ (Apr 2016)

Fujii T (nd) *Japan's coal policy and international contribution*. Available at: http://www.jcoal.or.jp/coaldb/shiryo/material/upload/1-1Keynote1_METI.pdf (nd)

Global CCS Institute (2016a) *Rotterdam Opslag en Afvang Demonstratieproject* (ROAD) Available at: http://www.globalccsinstitute.com/projects/rotterdam-opslag-en-afvang-demonstratieproject-road (Feb 2016)

Global CCS Institute, (2016b) *Tomakomai CCS project showcases Japanese technology leadership*. Available at: https://www.globalccsinstitute.com/news/institute-updates/tomakomai-ccs-project-showcases-japanese-technology-leadership (Mar 2016)

Green F, Stern N (2015) *China's "new normal": structural change, better growth, and peak emissions, Policy brief July 2015*. Available at: http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/2015/06/Chinas_new_normal_green_stern_June_2015.pdf (Jun 2016)

Hay L (2011) EPA's pending environmental regulations: challenges and new opportunities for the US electric generation fleet. *EM, AWMA*; 22-25 (Oct 2011) www.awma.org

Henderson C (2016) London, UK, IEA CCC, *personal communication* (Aug 2016)

Hutson N (2016) Research Triangle Park, NC 27711, USA, Energy Strategies Group, Office of Air and Radiation, U.S. Environmental Protection Agency (US EPA), *personal communication* (Aug 2016)

IEA (2010) *Power generation from coal measuring and reporting efficiency performance and CO_2 emissions.* Available at: https://www.iea.org/ciab/papers/power_generation_from_coal.pdf (2010)

IEA (2011) *Power generation from coal. Ongoing developments and outlook*. Available at: https://www.iea.org/publications/freepublications/publication/Power_Generation_from_Coal2011.pdf (Oct 2011)

IEA (2012) *Technology roadmaps high-efficiency, low-emissions coal-fired power generation*. Available from: https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHighEfficiencyLowEmissionsCoalFiredPowerGeneration_WEB_Updated_March2013.pdf (Oct 2012)

IEA (2016a) *The potential for equipping China's existing coal fleet with carbon capture and storage*, Paris, France, OECD/IEA, 95 pp (May 2016)

IEA (2016b) *Energy and Air Pollution. World Energy Outlook Special Report*. OECD/IEA, Paris, France, 262 pp (Jun 2016)

IEA CCC (2015a) *China Emission Standards*. Available at: http://www.iea-coal.org.uk/documents/82539/9516/China Oct 2015 (Oct 2015)

IEA CCC (2015b) *Japan Emission Standards* Available at: http://www.iea-coal.org.uk/documents/82549/9446/Japan (Jul, 2015)

IEA CCC (2015c) *USA Emission Standards*. Available at: http://www.iea-coal.org.uk/documents/82575/9515/United%20States%20of%20America (Oct 2015)

Ito S, Yokoyama T, Asakura K (2006) *Emissions of mercury and other trace elements from coal-fired power plants in Japan*. Science of the Total Environment: 368: 397-402 (2006)

Kahrl F (2016) *Coal-Fired Generation Overcapacity in China.* Available at: http://www.raponline.org/wp-content/uploads/2016/05/rap-coalcapacitychina-2016-feb.pdf (Feb 2016)

Keller M (2016) *Supercritical thinking: To achieve world's best performance, this coal fired power plant applies bullet like pressure to steam*. Available at: http://www.gereports.com/supercritical-thinking-this-coal-power-plant-applies-bullet-like-pressures-to-steam-to-achieve-worlds-best-performance/ (Jan 2016)

Kluger F, Marling T, Helmrich A (2016) *Energy Systems in Transition - Advancement of Steam Generator Technology is Key*. Paper presented at: 1st IEA CCC High efficiency low emissions coal-fired plant workshop, 23-25 May 2016, Tokyo, Japan. Available at: http://hele.coalconferences.org/ibis/HELE/home (May 2016)

Laković S, Mitrović D, Stefanović V, Stojiljković M (2012) *Coal-fired power Plant Power Output Variation Due to Local Weather Conditions DOI:10.1080/15567036.2010.495973 Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* Volume 34, Issue 23, p 2164-2177 (Sep 2012)

Li X, Sun R (2015) Windsor, London, UK, IEA Clean Coal Centre, *personal communication* (Oct 2015)

Li W, Yu C (2016) *Development path prospect of China's Advanced, High Efficiency Coal-fired Power plants*. Paper presented at: 1st IEA CCC High efficiency low emissions coal-fired plant workshop, 23-25 May 2016, Tokyo, Japan. Available at: http://hele.coalconferences.org/ibis/HELE/home, (May 2016)

Lockwood T (2015) *Advanced sensors and smart controls for coal-fired power plant*. CCC/251, London, UK, IEA Clean Coal Centre, 104 pp (Jul 2015)

Lockwood T (2016) *Blog: HELE workshop*. Available at: http://www.iea-coal.org.uk/site/2010/blog-section/blog-posts/hele-workshop (Jun 2016)

Makino K (2016a) *Promotion of investment for highly efficient power generation*, Stockholm Energy Charter Treaty Forum. Available at: http://www.sccinstitute.com/media/93407/keiji-makino.pdf (Feb 2016a)

Makino K (2016b) *Clean coal technology for future power generation*. Paper presented at: 1st IEA CCC High efficiency low emissions coal-fired plant workshop, 23-25 May 2016, Tokyo, Japan. Available at: http://hele.coalconferences.org/ibis/HELE/home (May 2016)

Makino K (2016c) JCOAL, Japan, *personal communication* (Oct 2016)

McMahon T, Ampriester T (2016) *W.A. Parish -Post-combustion CO_2 capture and sequestration project*. Paper presented at: Energy, Utility and Environment Conference (EUEC 2016), San Diego, CA, USA, 3-5 Feb (2016)

Mitsubishi Electric Corporation (2016) *Companies set up to run world's most advanced coal-fired thermal power plants in Fukushima.* Available at: http://www.mitsubishielectric.com/news/2016/1020.pdf (Oct 2016)

MPA (2013) *Status of advanced ultrasupercritical power plant designed for operation at 700°C in Germany*. Available at: http://seminar.mpa.uni-stuttgart.de/s-2013/Download/700%20C%20Plant.%20Vision%20of%20High%20Efficiency%20and%20Clean%20Energy%20Production.pdf (2013)

Nalbandian H (2008) *Performance and risks of advanced pulverised coal plant.* CCC/135, London, UK, IEA Clean Coal Centre, 70 pp (May 2008)

Nalbandian-Sugden H (2015a) *New regulatory trends: effects on coal-fired power plants and coal demand.* CCC/262, London, UK, IEA Clean Coal Centre, 116 pp (Dec 2015)

Nalbandian-Sugden H (2015b) *Climate implications of coal-to-gas substitution in power generation.* CCC/248, London, UK, IEA Clean Coal Centre, 92 pp (Apr 2015)

Nederveen M (2016) Coloradoweg 10, 3199 LA Maasvlakte, Dennmark, *personal communication* (Aug 2016)

NETL (nd) IGCC project examples. Available at: https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/project-examples (nd)

NeuCo (nd) CombustionOpt®. http://www.neuco.net/solutions-combustionopt-MATS-edition.asp (nd)

Peltier R (2013) *AEP's John W. Turk, Jr. Power Plant earns POWER's highest honor.* Available at: http://www.powermag.com/aeps-john-w-turk-jr-power-plant-earns-powers-highest-honor/

Peters H J (2010) *ReACT Reduces Emissions and Water Use*. Available at: http://www.powermag.com/react-reduces-emissions-and-water-use/ (Jan 2010)

Platts (2016) *Data base description and research methodology UDI World Electric Power Plants Data Base*, Platts, UDI Products Group, Washington, DC 20005 USA, 1 April 2016, pp 45 (2016)

Power Engineering (2016) *Kemper County Gasifier project hit with one more delay.* Available at: http://www.power-eng.com/articles/2016/12/kemper-county-gasifier-project-hit-with-one-more-delay.html?cmpid=enl-poe-weekly-december-09-2016&cmpid=enl_PE_PowerEngineeringE-Newsletter_2016-12-09 (Dec 2016)

Power Engineering International (2016) *China tackles overcapacity by halting coal power plant construction.* Available at: http://www.powerengineeringint.com/articles/2016/03/china-tackles-overcapacity-by-halting-coal-power-plant-construction.html (Mar 2016)

Power Magazine (2016a) *Amid scrutiny, Kemper IGCC project marks big syngas production milestone.* Available at: http://www.powermag.com/amid-scrutiny-kemper-igcc-project-marks-big-syngas-production-milestone/ (Jul 2016)

Power Magazine (2016b) *Kemper IGCC in-service date pushed back by a month.* Available at: http://www.powermag.com/kemper-igcc-in-service-date-pushed-back-by-a-month/ (Aug 2016)

Power Technology (2016) *Lean and clean: why modern coal-fired power plants are better by design.* Available at: http://www.power-technology.com/features/featurelean-and-clean-why-modern-coal-fired-power-plants-are-better-by-design-4892873/ (Jun 2016)

PRNewswire (2016) *Southern Company subsidiary announces another syngas production milestone at Kemper County energy facility*. Available at: http://www.prnewswire.com/news-releases/southern-company-subsidiary-announces-another-syngas-production-milestone-at-kemper-county-energy-facility-300329372.html (Sep 2016)

PROMECON (nd) *E.ON Benelux power station Maasvlakte, Rotterdam.* Available at: http://www.promecon.com/en/power/projects/e-on-benelux-power (nd)

Purgent R and Hatch H (2016) *U.S. Materials Program for Advanced Ultrasupercritical Steam Power Generation. Present Status of Component Test Facility and Commercialization Status*. Paper presented at: 1st IEA CCC High efficiency low emissions coal-fired plant workshop, 23-25 May 2016, Tokyo, Japan. Available at: http://hele.coalconferences.org/ibis/HELE/home (May 2016)

Reuters (2016a) *Rotterdam offers burial at sea for greenhouse gases.* Available at: http://www.reuters.com/article/us-environment-carboncapture-idUSKCN0ZZ1K4 (Jul 2016)

Reuters (2016b) *FACTBOX-Japan's construction plans for new coal-fired power stations.* Available at: http://uk.reuters.com/article/japan-carbon-plant-idUKL3N16X0RE (Apr 2016)

Rynek Energii Elektrycznej (2016*) Informacje o realizowanych i planowanych budowach i rozbudowach elektrowni/elektrociepłowni w Polsce*. Available at: http://www.rynek-energii-elektrycznej.cire.pl/st,33,335,tr,145,0,0,0,0,0,budowane-i-planowane-elektrownie.html#ostroleka Accessed July 2016

Santoianni D (2015) *Setting the Benchmark: The World's Most Efficient Coal-Fired Power Plants* http://cornerstonemag.net/setting-the-benchmark-the-worlds-most-efficient-coal-fired-power-plants/

Schneir S, Neary K (2016) *Investing in American energy. US DOE's Loan Office Program*. Paper presented at: Energy, Utility and Environment Conference (EUEC 2016), San Diego, CA, USA, 3-5 February 2016

Sloss L (2011) *Efficiency and emissions monitoring and reporting.* CCC/188, London, UK, IEA Clean Coal Centre, 67 pp (Sep 2011)

Sloss L (2012) *Legislation, standards and methods for mercury emissions control.* CCC/195, London, UK, IEA Clean Coal Centre, 43 pp (Apr 2012)

Sloss L (2015) *The emerging market for mercury control.* CCC/245, London, UK, IEA Clean Coal Centre, 75 pp (Feb 2015)

Sloss L (2016a) *Levelling the intermittency of renewables with coal.* CCC/268, London, UK, IEA CCC, 71 pp (Jul 2016)

Sloss L (2016b) *VGB Workshop on Mercury Control, Berlin, Germany, 15-16 June 2016.* Available at: http://www.iea-coal.org.uk/site/2010/blog-section/blog-posts/vgb-workshop-on-mercury-control-berlin-germany-15-16-june-2016?

Smouse S (2015) Windsor, London, UK, IEA Clean Coal Centre, *personal communication* (Oct 2015)

Smouse S (2016) USA, U.S. Department of Energy, *personal communication* (Nov 2016)

SWEPCO (2013) *John W. Turk, Jr. power plant.* Available at: https://www.swepco.com/global/utilities/lib/docs/info/projects/TurkPlant/TurkPowerPlantFactSheetrev3-21-13v3.pdf (Mar 2016)

Tarka T (2016) USA, Research & Innovation Center, National Energy Technology Laboratory, U.S. Department of Energy, *personal communication* (Sep 2016)

Tarka T, James R, Le P (2016a) *The integrated energy complex: opportunities for coal power generation in 21st century*. Paper presented at: Energy, Utility and Environment Conference (EUEC 2016), San Diego, CA, USA, 3-5 Feb 2016

Tarka T, Summers M, Turner M, Whire C (2016b) *Early mover CCS opportunities: coal to liquids via Fisher-Tropsch synthesis.* Paper presented at: Energy, Utility and Environment Conference (EUEC 2016), San Diego, CA, USA, 3-5 Feb 2016

Taylor D, (2015) '*One for all' energy policy for the EU*'. Available at: https://www.youtube.com/watch?v=UHx8VDCmEmg (Dec 2015)

The Japan Times (2015) *The same old energy mix.* Available at: http://www.japantimes.co.jp/opinion/2015/05/03/editorials/the-same-old-energy-mix/#.V2_vJGgrJEY (May 2015)

Then O (2016) VGB PowerTech e.V., Essen, Germany, *personal communication* (Nov 2016)

US DOE (2016) Carbon capture, utilization, and storage: Climate change, economic competitiveness, and energy security. Available at: http://energy.gov/sites/prod/files/2016/09/f33/DOE%20-%20Carbon%20Capture%20Utilization%20and%20Storage_2016-09-07.pdf 12pp (Aug 2016)

VGB (nd) *Examination of operational and failure behaviour of thick-walled components for high efficient power plants (HWT II)*. Available at: https://www.vgb.org/fue_projekt354.html (nd)

Wang Z (2016) *The current situation and prospect of coal-fired power plants clean development in China.* Presented at: 1st IEA CCC High efficiency low emissions coal-fired plant workshop, 23-25 May 2016, Tokyo, Japan. Available at: http://hele.coalconferences.org/ibis/HELE/home (May 2016)

Welford G (2016) *Life extension by biomass conversion.* Paper presented at: The conventional power boiler user group 2016 conference in Nottingham, UK, 8-9 Nov 2016

Williams J (2014) *America's best coal plants.* Available at: http://www.power-eng.com/articles/print/volume-118/issue-7/features/america-s-best-coal-plants.html (Jul 2014)

World Nuclear (nd) *Nuclear power in Japan* Available at: http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx Accessed: June 2016

Yamazaki T (2015) *Japan's electricity market reform and beyond.* Available at: https://www.iea.org/media/workshops/2015/esapplenaryjuly2015/Yamazaki.pdf

Zhang X (2016) *Emission standards and control of $PM_{2.5}$ from coal-fired power plant.* CCC/267, London, UK, IEA Clean Coal Centre, 80 pp (Jul 2016)

Zhu Q, (2016) *China – policies, HELE technologies and CO_2 reductions*, CCC/269**.** London, UK, IEA Clean Coal Centre, 76 pp (Aug 2016)

Zuberec, V (2015) Windsor, London, UK, IEA Clean Coal Centre, *personal communication* (Oct 2015)