Emerging markets for pollution control retrofits

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Preface

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

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

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, 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

Legislation is being implemented around the world to reduce emissions of pollutants from coal-fired power plants. For those countries that started to apply control strategies several years ago, the control technology market has evolved alongside the legislation in a somewhat piecemeal manner. This has meant that the majority of older plants in developed regions have applied controls in series: control technologies for particulates first, followed by controls for SO_2, and then controls for NOx. New legislation is introducing requirements for mercury and fine particulate control in some regions, often requiring further retrofitting of additional control systems. For those emerging regions that are just starting to bring in control requirements, there is the option of copying this piece-by-piece approach to control, or alternatively to apply newer technologies which can control several pollutants simultaneously. This multi-pollutant approach could be a cost-effective option in many regions. However, the applicability of different technologies varies. For example, regions with high ash and/or high sulphur coals may require different control strategies from those with intrinsically cleaner coals. Further, water and land availability along with the ability to appropriate funding for plant upgrades will all play a role in determining which technology will be applied at each plant. And so the control technology market that is currently expanding in Asia may differ significantly from that in North America and the European Union. The international marketing strategies for emission control technology manufacturers must take into account differences in performance standards, economic challenges, business traditions and a multitude of other factors which will affect whether a new control system is likely to succeed in a new region. This report summarises the potential markets for emissions control noting the areas for potential growth, such as China, Poland, India and Indonesia. Each has its own regional issues, financial and technical, which may pose challenges to international companies intending to expand into these areas.

Acronyms and abbreviations

ACI	activated carbon injection
ACIW	ACI injection into wet scrubber
AHPC	advanced hybrid particulate collector
BAT	best available technology
BHEL	Bharat Heavy Electricals Limited
BREF	best available technology reference document
CCS	carbon capture and storage
CDS	circulating dry scrubber
CEN	Comité Européen de Normalisation, European Standards Committee
CFBC	circulating fluidised bed combustion
COHPAC	combined hybrid particulate collector
CPP	Clean Power Plan, USA
DFGD	dry flue gas desulphurisation
DSI	dry sorbent injection
EFIC	electrostatic fabric integrated collector
EPL	Environmental Protection Law, China
EPPSA	European Power Plant Supplier Association
EPRI	Electric Power Research Institute, USA
ESFF	electrostatically stimulated fabric filter
ESP	electrostatic precipitator
FF	fabric filter or baghouse
FGD	flue gas desulphurisation
GAP	Green Aid Plan, Japan
GDP	gross domestic product
GEF	Global Environment Facility
GPT	gypsum pretreatment
HELE	high efficiency low emissions
ICETT	International Centre for Environmental Technology Transfer
IEA CCC	IEA Clean Coal Centre
IED	Industrial Emissions Directive, EU
IP	intellectual property
IPO	Intellectual Property Office, UK
iPOG	interactive pollution optimisation guidance
ITA	International Trade Administration
LCPD	Large Combustion Plant Directive, EU
LNB	low NOx burner
LNTFS	low NOx tangential firing system
LRTAP	Convention on Long Range Transboundary Air Pollution
LTE	low temperature economiser
MACT	Maximum Achievable Control Technology, USA
MATS	Mercury and Air Toxics Standard, USA
MEEP	moving electrode electrostatic precipitator
NECD	National Emissions Ceiling Directive, EU
NEDO	New Energy and Industrial Technology Development Organization, Japan
NID	novel integrated desulphurisation
OFA	overfire air
OSW	organosulphide addition to wet scrubber

OXI	oxidation catalyst
PRB	Powder River Basin
PM	particulate matter
PM_{10}	particulate matter below 10 µm in diameter
$PM_{2.5}$	particulate matter below 2.5 µm in diameter
SCR	selective catalytic reduction
SDA	spray dry absorber
SDS	spray dry scrubber
SNCR	selective non-catalytic reduction
SOFA	separated overfire air
TPP	thermal power plants
TFS	tangential firing system
UNEP	United Nations Environment Programme
WC	World Coal
WESP	wet electrostatic precipitator
WFDG	wet flue gas desulphurisation
WTP	water treatment plant
WTPS	water treatment plant with sludge concentration

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1 Introduction

Information on emerging markets for control technologies is often regarded as proprietary. There are numerous companies selling international market forecasts for thousands of dollars which they update annually. Many of these forecasts are based on the type of information discussed within this report – an understanding of current and impending legislation, data on technical specifications (of coals and plants), and an idea of other potential influencing factors (such as funding and water availability). And so, whilst this report may not lay out a quick guide to where sales may be made, it does provide an indication of the information needed and the path to follow to establish the potential for markets in different regions on a case by case basis.

For example, China has recently tightened emission standards to be amongst the most stringent in the world, and would appear to be a potentially huge market for emissions control technologies. But how much of this market is already predetermined? Which technologies are most appropriate for Chinese coals and coal-fired plants? How much of the market will be satisfied by local Chinese manufacturers and how much will actually remain open to potential international sales? There is no simple answer. Rather, the situation requires a more detailed and considered review of the information available in order to fully understand what markets emerge and what proportion of that market is actually open to international bidding. This report reviews the different factors which must be taken into account in order to predict potential emerging markets. Although some effort is taken to indicate trends in current and impending markets, it is important to realise that these change rapidly with factors such as emerging legislation and new technological breakthroughs.

The first consideration in terms of pollution control markets is the technology available and what it can do. For example, at present there are two kinds of technical routes for pollution control in coal-fired power plants:

- conventional approach – where technologies designed to remove one specific pollutant are combined in series to remove several pollutants in order to meet all the required emission regulations. These distinct, in series, systems have emerged as a consequence of the way that emissions legislation has evolved – in a separate and piecemeal manner for individual pollutants over several decades;
- multi-pollutant control systems – are more recently developed. Technologies have been designed to remove two or more of the principal regulated pollutants in a single reactor or in a single system which combines several different technologies. The applications of many of these integrated removal technologies are in their early stages and most have not been deployed in large numbers on coal-fired power plants. Further, it would appear that many of these systems are designed as 'polishing technologies' – systems designed to be additional to conventional control systems to provide more intensive flue gas cleaning to comply with tightening emission legislation and lower emission limits. However, for some countries, India for example, which are stepping up to apply emissions control for all pollutants simultaneously, a combination of well-chosen flue gas cleaning systems combined with

compact multi-pollutant control systems may be more appropriate than the application of several large, separate systems in series.

This report concentrates on summarising information from previous IEA Clean Coal Centre (IEA CCC) reports and updating it with newer data and information on emerging markets. This document will therefore be more of a discussion paper than many reports and, should the interested reader seek more detailed information, they will be referred to the appropriate, complementary, IEA CCC documents.

Chapter 2 of this report summarises the common control technologies available in the market place and gives an indication of the means by which the most appropriate method is selected. In some cases, the coal type and plant configuration may determine which approach is most suitable. In others, cost, space, water availability and other issues may be more important. Emerging new multi-pollutant systems are discussed in Chapter 3. Chapter 4 then looks at the selection process, focusing on the factors which may vary from site-to-site and country-to-country. These include the relevant legislation, the plant age and design, and coal characteristics and the economics of the region. The international market is considered in Chapter 4, with a discussion of technology transfer, funding mechanisms and the options for import versus national production of control technologies. Finally, Chapter 5 includes country studies, highlighting regions where new import markets may be emerging.

2 Pollution control technology options

The IEA CCC has produced numerous detailed reports on emission control systems for coal-fired power plants. Information about the reports can be found at: www.iea-coal.org/site/2010/publications-section/reports. They include:

Particulate matter (PM) control

- Zhang (2016) *Emissions and control of $PM_{2.5}$ from coal-fired power plants*, CCC/267
- Nicol (2013) *Recent developments in particulate control*, CCC/218
- Zhu (2003) *Developments in particulate control*, CCC/72
- Wu (2000) *Prevention of particulate emissions*, CCC/40
- Soud (1995) *Developments in particulate control for coal combustion*, IEACR/78

NOx control

- Nalbandian (2009) *NOx control for coal-fired plant*, CCC/157
- Wu (2002) *NOx control for pulverised coal-fired power stations*, CCC/69
- Nalbandian and Fukasawa (1996) *Developments in NOx abatement and control*, IEACR/89
- Sloss (1991) *NOx emissions from coal combustion*, IEACR/36

SO_2 control

- Carpenter (2012) *Low water FGD technologies*, CCC/210
- Zhu (2010) *Non-calcium desulphurisation technologies*, CCC/170
- Zhu (2006) *Trends in SO_2 emissions*, CCC/115
- Fernando (2003) *SO_3 issues for coal-fired plant*, CCC/72

Multi-pollutant control

- Carpenter (2013) *Advances in multi-pollutant control*, CCC/227
- Nalbandian (2004) *Air pollution control technologies and their interactions*, CCC/92

The interested reader is recommended to download these free reports for more detail. The following sections summarise these reports, focusing on the main performance characteristics of the various pollution control systems and the selection process which determines the market for each. Updates on new systems are included where possible.

Although coal cleaning and blending are options to increase combustion efficiency and reduce emissions from some coal-fired plants (Sloss, 2014), this report concentrates on technologies which can be retrofitted onto existing plants. Some of the factors discussed in this report will also be relevant to the potential markets for emissions monitoring equipment. Where an emission limit is set and a reduction in emissions is required, the effectiveness of any control technology will be evaluated using emission measurement and monitoring systems. According to the International Trade Administration (ITA, 2016), a "substantial segment" of the air pollution control industry is comprised of monitoring technologies, including instrumentation and software. For example, the US industry revenues for air pollution control in 2014 totalled US$19.4 billion, including equipment, instruments, and attendant services. Of this, air quality monitoring equipment amounted to US$1.3 billion. Over and above this the US revenues for environmental consulting and engineering amounted to US$28.9 billion in the same year. With numbers this large, it is not surprising that many major players in the market are looking to expand into international sales.

2.1 Particulate control systems

The following sections briefly review the technology options for particulate control retrofitting, looking at the factors which are used to decide between these options.

2.1.1 Technical options

There are two types of particulate control systems which currently dominate the market for coal-fired utilities – electrostatic precipitators (ESP) and baghouses (also known as fabric filters). These systems commonly provide at least 99.9% particulate control, often more.

ESP work by using electrostatic forces to attract particles to a charged field. The collected particles are then periodically shaken off into a hopper below. ESP performance can be improved with flue gas conditioning, often using sulphur trioxide (SO_3), to reduce the resistivity of some ash particles. New techniques are being developed to enhance the performance and operation of the electrostatic fields, such as pulse energisation (pulse-jet; where compressed air is used to rap ash from the filter in a more aggressive manner than in standard baghouse systems). Pulse-jet systems are becoming increasingly popular. Newer and more novel approaches, such as electromagnetic multi-duplex dual zoning, ion blasting and lentoid electric fields, appear to improve the capture of particulates, especially fine particles but do not seem to be commercially significant as yet (Zhang, 2016).

Wet ESP (WESP) have lower temperatures (around 50°C versus 120–450°C for standard ESP systems) and collected particles are washed rather than shaken off the electrical plate. These systems are well established in the commercial market, especially in China. WESP have excellent capture efficiencies for fine particulates (PM_{10} and $PM_{2.5}$) and also for sulphur and other soluble acid aerosols such as halogens and so are considered a multi-pollutant control technology (*see also* Section 2.4). WESP can be in either horizontal or vertical configurations which makes them easier to retrofit in plants with space constraints (Zhang, 2016).

Abe (2016) discusses the Mitsubishi Hitachi MEEP (moving electrode electrostatic precipitator) system. The system incorporates several static ESP fields followed by a moving/rotating field which moves the dust collection surface past brushes to remove particulates. The MEEP system is reported to take up less space and does not have the dust resistivity issues of a traditional ESP system. The MEEP is being demonstrated at a full-scale plant in Uttar Pradesh, India.

Baghouses are simpler than ESP systems in that they comprise a filter and a rapping/release system. Particulates are caught on the filter and then, after a pre-defined collection period, the filter is agitated to drop the trapped fly ash into a hopper below.

Hybrid systems, which combine ESP and baghouses, have been developed. These include the advanced hybrid particle collector (AHPC), compact hybrid particulate collector (COHPAC) and the electrostatically stimulated fabric filter (ESFF) amongst others. However, although COHPAC has been demonstrated at full scale in several plants (1700 MW to date on coal-fired boilers and waste to energy incinerators; Zhang, 2016), it could be argued that it is not an option that would be considered for simple particulate control alone but rather as part of an advanced approach to multipollutant control (*see* Section 2.4). As such, COHPAC systems are more likely to be incorporated into new or recent plants to ensure payback on investment. Zhang (2016) also discussed several types of advanced particulate control systems using techniques such as wet agglomeration, magnetic aggregation and thermophoretic deposition. However, these systems are largely still experimental.

2.1.2 Selection criteria

Benesch (2013) gives a simple summary of the major differences between ESP and baghouses, in terms of suitability for purpose, as shown in Table 1.

Table 1 Comparison of baghouses and ESP (Benesch, 2013)

Parameter	Fabric filter/baghouse (pulse-jet)	ESP (horizontal flow)
Gas flow	No limitation	No limitation
Flue gas temperature	Critical: bag material may clog if close to dew point	<450°C, critical if close to dew point because of corrosion
Dust concentration	No limitation	No limitation
Dust resistivity	No influence	Most critical parameter for ESP sizing
Particle size distribution	May have issues with penetration of very fine particles, treatment may be required	May have resistivity and cohesion issues requiring suppression of re-entrainment
H_2O and acid dew points	Sensitive for some fabrics which may result in blockage	Positive effect through conditioning but may induce corrosion
Required base area	~43 m^2/m^2 (7 m bags), ~65 m^2/m^2 (8 m bags)	~80 m^2/m^2 (16 m active height)
Specific power consumption	1.5–3.0 kW/(m^3/s) (including ID fan)	0.2–1.5 kW/m^3/s) depending on ash resistivity
Lifetime of Internals	5 y for bags, 15 y for cages	15-20 y
Separation efficiency	Higher	High
Dependency on coal quality	Low	High
Dangers	Risk of fire at high flue gas temperature and high carbon content	Electricity
Maintenance	Online	Offline
Additional reactions	Yes, in dust layer (important for mercury capture)	No

As discussed by Benesch (2013), there is not a huge difference in cost between ESP and baghouses, with the decision on which to install being based more on plant- and coal-specific factors. ESP have the advantages of low maintenance over a long lifetime with low energy consumption and operation costs. However, they have issues with coals which produce ash of high resistivity (such as low sulphur coals) and therefore work best when tuned to a particular coal. But they do take up a lot of plant space. Baghouses work well on almost any coal and can enhance the capture of other pollutants, especially mercury, due to extended periods of ash surface availability. However, the bags have a limited lifespan and require more maintenance and replacement work than ESP. Baghouses can also have issues with changes in temperature and boiler tube leakage.

Benesch (2013) describes the ways to optimise the performance of both ESP and baghouses to make each applicable in almost any situation. This means that, should a different coal be used, most plants will be able to alter the performance of existing control equipment to maintain particulate control requirements. However, when making a decision on an original purchase, the factors discussed in Table 1 will be taken into account. Nicol (2013) noted that the performance of a specific particulate control device on any plant cannot be guaranteed – initial testing and assessments are necessary to ensure that the selected system will work with the specific challenges presented by each site on a case-by-case basis.

During the 1990s, China favoured the installation of ESP for their challenging coals, and 82% of the coal capacity in 2003 was installed with precipitators. However, since the first installation of a baghouse in China in 2001, the use of filters has grown significantly (Liqian and others, 2009). Chinese coals differ widely in their composition, from 10–58% ash, 0.14–5.3% sulphur and 0.8–9% moisture. Liqian and others (2009) summarised the different Chinese coals used in the 1990s and 2000s, noting which would be best controlled by an ESP and which would require a baghouse.

Some plants in the USA have recently converted from ESP to baghouse systems for several reasons, including in the somewhat dated, but still relevant, paper by Lugar and others (2008):

- ESP cannot meet certain outlet emission limits, especially opacity requirements. (Opacity is a visibility issue associated with plumes and is a measure only controlled in the USA). This may occur as a result of a fuel change to lower sulphur coal but also as a result of ageing equipment.
- Changes to fuel, such as switching to a lower sulphur coal, can adversely affect ESP performance due to changes in the resistivity of the ash.
- Addition of flue gas desulphurisation (FGD) system upstream or downstream will require a minimum performance of the ESP to avoid ash issues.
- Many ESP systems cannot cope with increased load due to the addition of sorbent (*see* Section 2.4 on mercury control).
- Issues with tightening particulate emission regulations, especially $PM_{2.5}$ (*see* Section 2.4).

Lugar and others (2008) also provided a relevant list of advantages of converting an ESP to a pulse-jet fabric filter:

- lower cost than replacing with a new ESP or baghouse;
- can be installed in the existing ESP space/footprint;
- minimum ductwork replacement or addition;
- reuse of existing hoppers and ash conveyance system;
- fuel flexibility – the fabric filter is more 'forgiving' than an ESP;
- can cope with sorbent injection for mercury control; and
- more suitable for compliance with $PM_{2.5}$ emission standards.

Lugar and others (2010) report on the conversion of the ESP system at the Big Stone Plant, Unit 1, in South Dakota. Operators at the plant, which fires Powder River Basin (PRB) coal, had determined that a pulse-jet fabric filter would be much more suited to the plant to improve performance (induced draught fan pressure drop limitations) and for compliance with anticipated fine particulate matter legislation.

Similar to the USA, some plants in India are considering a move from ESP to baghouses (Zhang, 2016). Although, in the past, there were problems with the cost of maintenance of baghouses and the filter bags, it seems that new designs have made them more reliable and affordable. There is also the aforementioned consideration that baghouses appear to offer significant advantages for mercury control, especially when sorbents are used.

A previous report by the IEA CCC (Nicol, 2013) noted that ESP accounted for 85% of the particulate control systems in Germany whereas baghouses were more favoured in Italy. Many plants in Australia and South Africa, which had initially been installed with ESP, have switched to baghouses to cope with low sulphur and high ash coals. Nicol (2013) concluded that ESP systems dominated the existing global fleet and new sales of particulate control systems. However, since then there seems to be a significant move from ESP to baghouses in countries such as the USA, South Africa, Australia, and India, as mentioned above, and so the overall balance may be changing. Studies in China suggest that the existing ESP fleet is largely able to cope with existing and impending legislation and, for those plants which may have issues, adding another ESP field would be adequate to solve the problem. For the Chinese market, at least, a six-field ESP system is half the cost of a baghouse over a 10-year period. This may be partially due to the fact that China produces ESP systems and has a significant research, development and manufacturing base for them (Nicol, 2013). Despite this, as in the USA, in recent years ESP systems have been replaced with fabric filters or pulse-jet bag filters, with ESP in the Chinese fleet dropping from 95% in 2010 to 69% in 2015 and baghouses increasing from 5% to 31% during the same period.

So the choice of particulate control system appears, in the past, to have been determined by the nature of the coal being used, with coals producing ash with low resistivity proving a challenge for some ESP systems. However, with a move towards multi-pollutant control requirements, many plants in western economies appear to be moving towards baghouses, since they offer better capture, especially when using sorbents. Some plants in China appear to be upgrading existing ESP systems or adding WESP systems to achieve similar multi-pollutant control, but the country is also showing an overall trend towards fewer ESP systems and more baghouses.

2.2 Sulphur control systems

Sulphur controls have been necessary from the 1960s onwards in many regions due to the issue of acid rain. Control systems have been discussed in several previous reports by the IEA CCC (Carpenter, 2012, 2013; Zhu, 2010; Fernando, 2003).

2.2.1 Technical options

There are three main options for sulphur control at coal-fired power plant (Carpenter, 2013):

- Low sulphur coal (either naturally low or made low sulphur by coal washing and cleaning techniques which are outside the scope of this report).
- Wet FGD systems – reagents (such as lime, limestone or similar materials) are mixed with water. Wet FGD systems are far more common than dry FGD systems. Wet FGD systems account for over 80% of the current global installations of sulphur flue gas control.
- Dry FGD systems – reagents such as limestone and lime are directed into flue gases. The performance may be limited if the temperature is not controlled (Johansson, 2012). Dry scrubbers account for under 10% of the total installed FGD capacity worldwide.

Wet scrubbers were developed in the late-1960s to use limestone or similar material to capture sulphur in a dry or semi-dry form. In many systems, gypsum is produced as a saleable by-product. In some regions, where there is an active gypsum market, this can bring in valuable additional revenue for the plant. In other regions, excess gypsum becomes unsaleable waste and adds to disposal costs. This can have a significant effect on plant economics.

Johansson (2012) summarises the traditional options for sulphur control at coal-fired plants in Figure 1.

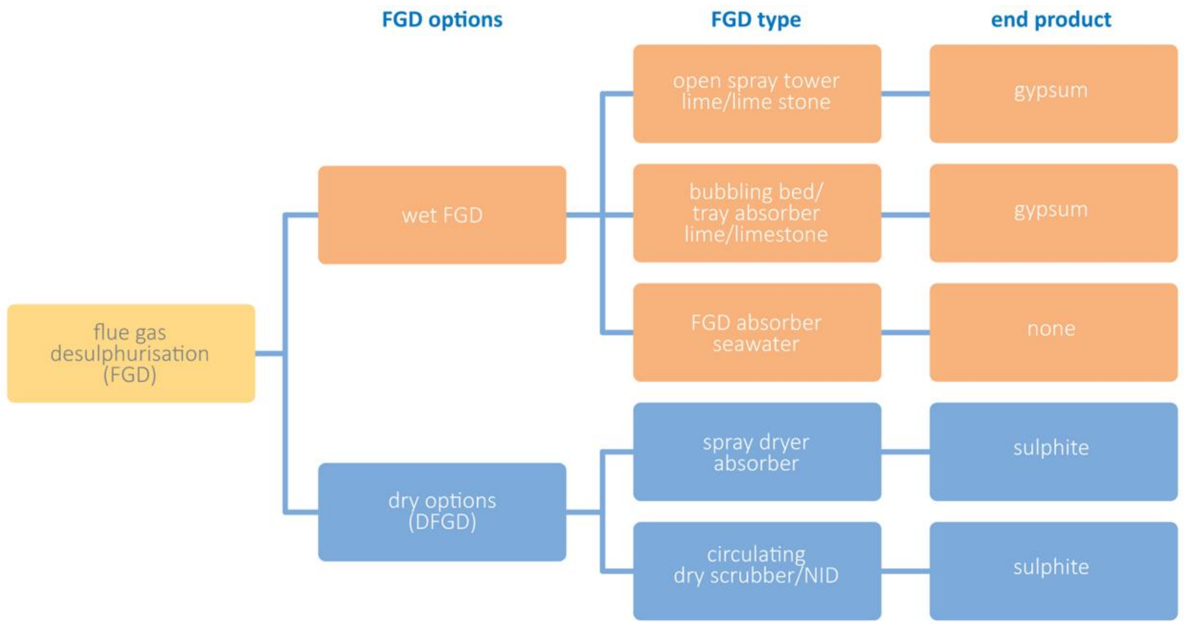

Figure 1 Common principles for FGD (Johansson, 2012)

As already mentioned, wet FGD systems, the most popular form, produce gypsum as a potentially saleable by-product. This is not the case for seawater FGD systems where seawater acts as the absorber and the sulphur is released into the effluent water. The world's largest seawater plant was installed at the 2 x 1000 MW Haimen plant in China, in 2009 and achieves 95% sulphur removal (Johansson, 2012). The Shenhua Company in China is developing its own high efficiency sulphur scrubbing system based on seawater and plans to use this at many of its coastal plants. Emissions below 2.76 mg/m^3 can be achieved at some plants based on seawater scrubbing (Shumin, 2015).

Dry FGD systems are less common. Advanced dry FGD systems are being developed, such as DFGD (dry FGD) with controlled temperature and comprise a circulating dry scrubber or NID (Novel Integrated Desulphurisation), in combination with a fabric filter (Johansson, 2012).

Both wet and dry FGD systems have multi-pollutant control effects, as they reduce emissions of particulates and soluble trace elements such as mercury, sometimes significantly. This is discussed more in Section 2.4.

2.2.2 Selection criteria

The selection of FGD systems will clearly be made based on many factors including affordability and availability. Technical considerations include (Johansson, 2012):

- there must be the option to release or treat water with elevated concentrations of halides such as chlorine and bromine, and possibly other trace ingredients;
- if it is a dry system which uses particulate control (such as DFGD) then either the existing particulate control systems must be adequate or must be adjusted or replaced accordingly;
- potential issues with the plume (increased opacity, an issue in the USA) mean that SO_3 may require specific control or the plume may require reheating to improve dispersion;
- availability of affordable, good quality quicklime; and
- seawater FGD systems will, of course, require coastal access.

Table 2 summarises the main differences between the different sulphur control technologies.

Table 2 Key parameters for different FGD systems (Johansson, 2012)			
	Dry FGD	**Seawater FGD**	**Limestone FGD**
Absorber	Circulating dry scrubber or SDA	Packed tower	Spray tower
Features	Low investment cost Dry by-product Small footprint Multi-pollutant control	No reagent No by-product	High efficiency spray zone Low cost reagent By-product flexibility
Reagent	Lime	Seawater	Limestone
By-product	Landfill	Seawater	Marketable gypsum or landfill
Sulphur, %	<4.5 (dry scrubbing system)	<1.5	<6
Removal efficiency, %	–98 (dry scrubbing system)	<98	<99
Relative capital cost	0.7	0.8	1.0
Power consumption, % (including booster fans)	0.7	0.7–1.5	1.0–2.0
Absorbent cost, €/t	80	0	20
By-product cost, €/t	5–10 (disposal)	0	5–10 (disposal) 5 (sale)

Dry and seawater FGD systems have the potential to be cheaper to install and may require less power during operation than wet FGD systems. However, dry FGD systems have significant absorbent costs with no potential for sale of the by-product. Absorbent costs are lower for wet FGD systems and the sale of gypsum can significantly offset this cost (by around 25%). Wet FGD systems are more suitable for high sulphur coals and can achieve the highest control efficiencies even with this additional challenge. Wet FGD can be more cost-effective at coastal sites but can cause local issues with changes to water quality.

In terms of cost, more advanced systems such as DFGD will require greater investment and/or a longer pay-off period. Such systems will therefore be more suitable for younger plants with a longer remaining operational life. Costs, both capital and operational expenditure, will also be proportional to plant size. Carpenter (2013) notes that there was little difference in cost between spray dry scrubber systems (SDS) and circulating dry scrubber systems (CDS). There are structural and space considerations for a CDS system, which requires a large, elevated fabric filter. However, SDS systems tend to be larger and may have extra equipment requirements in the form of slurry recycle systems. CDS systems require 20% more reagent than SDS systems under the same conditions and the operating costs for CDS can also be higher, with more waste to be landfilled.

Figure 2 shows the current uptake of sulphur control technologies for different plants (Johansson, 2012).

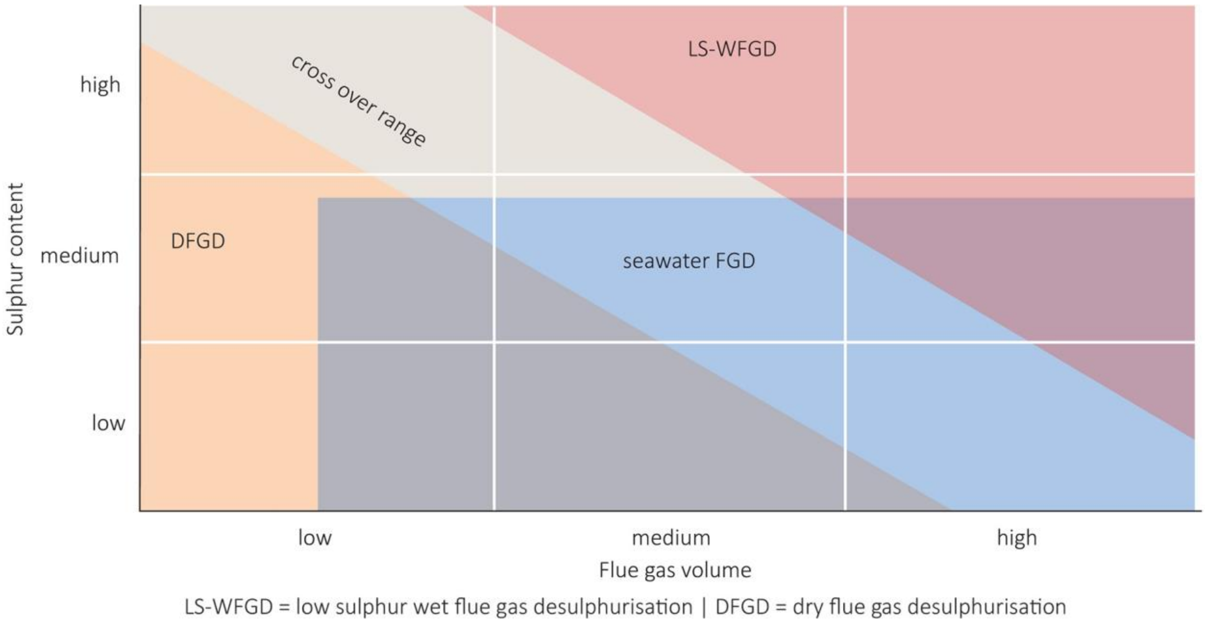

Figure 2 FGD technology selection (Johansson, 2012)

The figure indicates that, currently, dry FGD systems are more favoured for plants with low flue gas volume (smaller plants) and plants firing coals with lower sulphur contents although, according to Johansson (2012), dry scrubbing systems such as NID have expanded the range of dry FGD systems to larger plants. Wet FGD systems are more popular on larger plants with higher sulphur coals. Seawater FGD systems can cope with high flue gas volumes but may struggle to control emissions efficiently from plants firing higher sulphur coals. Gore have developed a catalyst-based system, available in scalable, modular form, for both sulphur and mercury control, generating sulphuric acid instead of solid wastes and with a significantly lower water requirement than wet FGD systems. The system is also passive and so therefore does not reduce plant output (Kolde, 2016; *see also* Chapter 3).

For countries that have issues with limited water availability, there are desulphurisation systems which require little or no water, such as dry sorbent scrubbers and many of the multi-pollutant systems discussed in Chapter 3. Challenges for pollution control in countries with water restrictions are discussed in more detail in the IEA CCC report by Carpenter (2015).

The potential for revenue from by-product sales is often an important issue in the selection process. Gypsum sales can be profitable in regions where gypsum is either not available or relatively costly. According to He and Lee (2014) gypsum marketing in the USA had a significant effect on the control technology used and the amount of sulphur captured in this waste form. However, if gypsum is not a valued commodity near the plant, then it becomes a waste issue which will count against the selection of a wet FGD system. Alternative reagents to lime are possible, with some new systems focusing on ammonia scrubbing. These systems can produce saleable fertiliser by-products rather than gypsum, and are discussed more in Chapter 3.

2.3 NOx control systems

NOx control systems have been reviewed in several previous IEA CCC reports (Carpenter, 2013; Nalbandian 2002, 2004; Zhang, 2016).

2.3.1 Technical options

NOx control systems can be broadly divided into two main categories:

- Primary measures (changes to the boiler) – low NOx burners (LNB), overfire air (OFA) or air staging. Primary combustion measures control and limit the production and release of NOx from the combustion zone by promoting its reduction to molecular nitrogen.
- Flue gas control systems, further divided into selective catalytic reduction (SCR); and selective non-catalytic reduction (SNCR) systems. SCR systems use a catalyst to reduce the NOx to nitrogen whereas SNCR uses a nitrogen containing reagent such as ammonia to reduce the NOx. SCR systems can work at lower temperatures than SNCR due to the presence of the catalyst.

Table 3 shows the most commonly available NOx control technologies, as summarised by Sinha (2016).

Table 3 NOx control technologies (Sinha, 2016)

Technology	During combustion	Post-combustion	
	Combustion modification	SNCR	SCR
Details	Low NOx burner; wind box modification; overfire air	Anhydrous/aqueous ammonia or urea	Plate/honeycomb catalyst; anhydrous/aqueous ammonia or urea
Reduction efficiency	20–60%	25–40%	>90%
Installation cost	Low	Moderate	High
Operational cost	None	High (mainly reagent cost)	High (auxiliary power, reagent cost and catalyst replacement)
Process of NOx reduction	Staging of combustion air	Chemical breakdown	Chemical breakdown
Temperature required	NA	870–1100°C	300–400°C

Globally, SCR systems are the most popular flue gas control option for NOx, mainly because they can achieve significantly greater reductions in NOx emissions than alternative approaches.

2.3.2 Selection criteria

As shown in Table 3, low NOx burners and other changes in boiler configuration to control or reduce NOx emissions are commonly less expensive than SCR or SNCR systems and require a smaller footprint area for retrofitting. However, the use of combustion controls will be limited by such factors as the type of existing boiler and the coal type and may not be adequate for compliance in areas with tighter emission limits. Plant operators will commonly try to work out, through modelling or testing, whether emissions can be reduced by changing the boiler configuration alone (with low NOx burners or air staging). Although boiler modification will require some plant downtime, there is no additional plant space required and, once the modifications have been made, there is no ongoing running cost. However, boiler and burner modifications can only provide up to around 40% NOx control on most plants.

SCR and SNCR systems require plant space for retrofitting, and power for operation, probably less than 0.5% of the plant power. Installation costs for SCR systems are often higher than for SNCR systems (around twice as much during the 1990s) and running costs, including maintenance of catalyst materials, are also higher (Nalbandian, 2004). Unlike boiler modifications, SCR systems also have a larger footprint space at the plant. Ash accumulation on SCR catalysts can be an issue at plants firing high ash coals. This could be an important consideration for India where indigenous coals are notoriously high in ash (*see* Chapter 4). The ash in coal contributes to plugging of pores in the catalyst surface and also to erosion from silica and alumina, which makes up over 85% of the ash in Indian coals (Sinha, 2016). The issue of NOx control at plants firing high ash coals is the subject of a new IEA CCC report which should be available at the end of 2017.

Figure 3 shows the potential emission reduction rate of different NOx control technologies applied to plants firing different coal types.

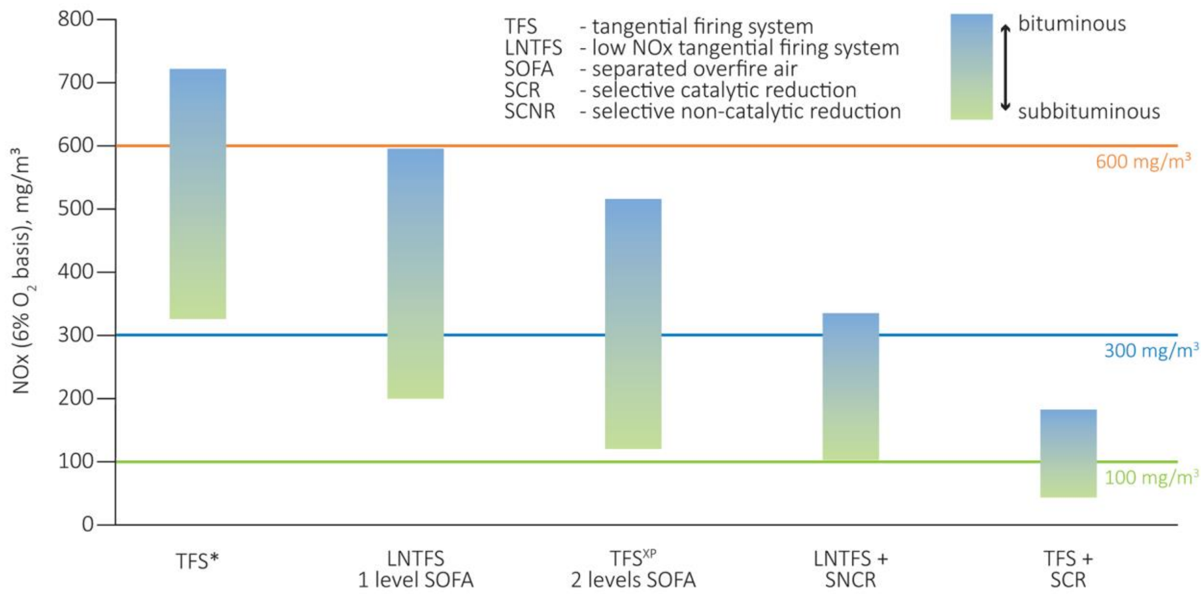

Figure 3 Performance of NOx control technologies (Sinha, 2016)

As can be seen in Figure 3, reducing emissions from subbituminous coals is easier than for bituminous coals due to the combustion characteristics of the coals. Combining any of these combustion modifications with flue gas control (SNCR or SCR) can potentially control emissions to below 100 mg/m^3, depending on the coal characteristics and emission limit requirements.

2.4 Combining and enhancing existing pollutant control systems

Defining a control system as being applicable to just one pollutant (such as FGD for sulphur control) can be somewhat misleading as all of the control technologies used at coal-fired plants achieve reduction of more than one pollutant due to co-benefit effects:

- particulate systems will capture any sulphur or trace elements (including mercury) which are associated with particulates or which will attach to any solid materials being captured in an ESP, baghouse or similar technology;
- NOx control systems such as SCR catalysts will oxidise mercury and enhance its capture in downstream control systems; and
- FGD systems will also capture some additional particulate material together with any trace elements associated with these solids and soluble material such as oxidised mercury.

As discussed in several previous IEA CCC reports (Sloss 2012, 2015a), mercury can be captured by almost any control technology in a coal-fired plant and even those technologies which do not capture mercury (such as SCR systems) can enhance mercury capture in downstream technologies. Combining ESP with wet FGD achieves 40–85% mercury removal in many plants, depending on the oxidation chemistry of the coal, especially the native halogen content (Shumin, 2015; Vosteen, 2017).

Table 4 shows the potential control of mercury from combinations of control technologies.

Table 4 Mercury control options

Approach	Capital cost	O&M cost	Comments
Oxidation additives (*see* Section 2.4.1)	Very low	Low	Halogenated additives significantly increase Hg oxidation and capture (potential corrosion must be managed)
Re-emission control additives	Very low	Low	Potential for re-emission of Hg should be mitigated
SCR catalyst, with downstream FGD	Low	Low	(Cost estimate only refers to the prioritising of an Hg suitable catalyst). May require coal blending to maximise the effect. Additives may be required to prevent re-emission
ACI injection (*see* Section 2.4.2)	Low	Low to moderate	Preservation of ash quality sometimes an issue, but becoming less so with newer sorbents

The amount of mercury control which can be achieved with each of these approaches is not listed as it is extremely variable and is affected by such factors as coal chemistry (*see* Section 2.4.4). However, most commercial suppliers will work with plants on a case-by-case basis to modify performance of their systems and even combine approaches to ensure that the final system provides the required level of pollutant control. In systems using bromine, consideration of potential enhanced corrosion issues must be built into the operation and management plan. Note that the mercury emission limit for countries such as the USA is based on a rolling average basis and not a strict one-hour limit. This gives a little leniency to forgive short and transient episodes where the emission limit is exceeded.

A separate report from the IEA CCC (Zhang, 2016) looks at control of fine particulates (PM_{10} and $PM_{2.5}$). However, as emphasised in Zhang's report, most fine particulates are either primary particles, or secondary particles formed from sulphates and nitrates. And so control strategies to reduce emissions of fine particulates are the same as those to enhance and maximise capture of particulates, SO_2 and NOx.

As emission limits tighten and new pollutants become targeted (mercury, trace metals, halogens, fine particulates), existing control systems may be able to provide some control but may not be able to reduce emissions of all pollutants simultaneously, even when several technologies are used in sequence. There are several options for multi-pollutant control, which include:

- working with existing systems to enhance co-benefit multi-pollutant control (covered in this section); and
- systems which have been developed specifically for multi-pollutant control (*see* Chapter 3).

And so defining a system as being a multi-pollutant control system can be misleading. All systems have the potential to control more than one pollutant but, in general, older systems were designed to control one pollutant and any extra control is a beneficial side effect. However, as emission legislation increases in stringency, technology manufacturers are learning to adjust their systems to enhance these co-benefit effects and to market their systems as multi-pollutant control options.

Table 5 shows the technologies available for compliance under current US legislation with the pollutants controlled and the time required for retrofit (Hutson, 2016).

Table 5 Controls available for co-benefit pollution reduction (Hutson, 2016)

Emission control system	Primary pollutant controlled	Co-benefit reduction	Installation times (design to installation), months	Outage time, weeks
Baghouse	PM, Non-Hg metals	Hg (with or without ACI), acid gases (with DSI)	12–24	1–4
ESP upgrade	PM, Non-Hg metals	Hg (with ACI), acid gases (with DSI)	6–24	0–4
DSI	Acid gases (including halogens)	SO_2, SO_3, SeO_2	9–12	None
Dry scrubber	Acid gases (including halogens)	SO_2, SO_3, SeO_2, Hg	24–36	1–4
Scrubber upgrades	Acid gases (including halogens	SO_2, SO_3, Hg	12–36	4–8 (in two parts)
ACI, activated carbon injection	Hg	–	12–18	None
Oxidant addition	Hg		3–12 months	None*

* plant specific – discussed more in Section 2.4.1

The table emphasises that most retrofitted control technologies are now considered multi-pollutant technologies to some extent due to the co-benefit capture of additional pollutants. Table 5 also indicates that there is a significant time requirement for upgrading or installing new control systems to a plant which must be taken into account. There is no clear way to determine which system is best in each instance. Unlike the similar tables for SO_2, NOx and particulate control comparisons, it is not possible to predict the effectiveness of one system for a collection of pollutants, all of which will vary with coal chemistry and plant configuration.

2.4.1 Enhancing mercury capture in existing systems with oxidants

In most situations, the major pollutants (particulates, SO_2 and NOx) are controlled by standardised equipment, as discussed above, and new requirements for mercury control are the major impetus behind modification and enhancement of this equipment. Oxidised mercury is sticky and soluble and is therefore relatively easy to capture in existing control systems which provide some form of sorbent activity (such as unburnt carbon in ash) or a solution for mercury to dissolve in (such as in a wet FGD).

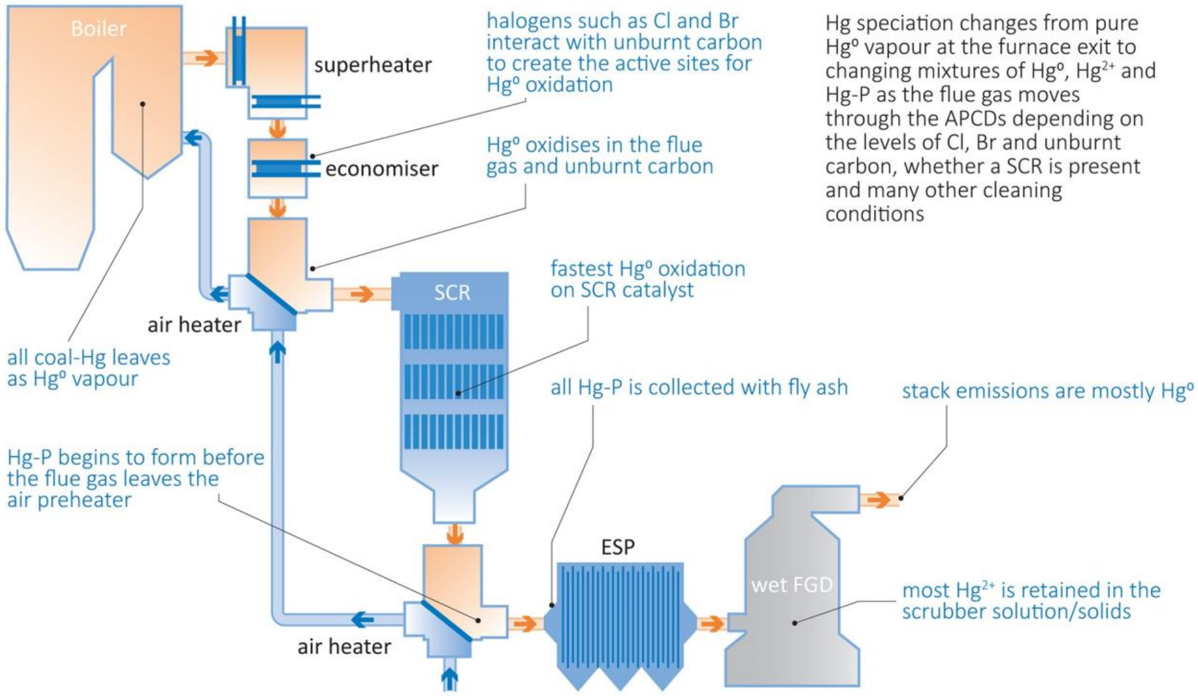

Figure 4 Mercury behaviour through a coal-fired power plant (Jozewicz, 2016)

Figure 4 indicates the complex chemistry of mercury through a coal-fired plant and the various interactions it can have with surfaces, catalysts and ash. Mercury can be oxidised at several sites during its passage through the plant and, in the oxidised form, can be caught in fly ash, on sorbents, or in the FGD waste materials. Unfortunately, this capture does not work for elemental mercury. The most common means of enhancing mercury capture in existing flue gas control systems (co-benefit effects) is by the use of oxidants. Halogen addition in the form of easy to handle halides such as calcium bromide ($CaBr_2$) is an effective way of enhancing mercury capture and bromine (released from the bromine salt) is the most commonly used halogen as it has the greatest oxidation potential for mercury. The catalysts used in SCR systems can also act to oxidise mercury, although this can have a negative effect on the catalyst lifespan. Addition of a sorbent, especially a sorbent activated with a halogen, will add another surface for mercury to attach to and thus capture mercury in a solid form.

The most popular commercial oxidant in use is bromine or bromine based materials. There have been a few law suits over the patenting of bromine-based approaches (*see* Chapter 4) with several companies offering similar systems. However, the original patent for bromine use is held by Vosteen Consulting Ltd in Germany. The addition of bromine has been applied at many plants – for example, Plant Millar of the Alabama Power Company, USA, has injected $CaBr_2$ directly onto the coal being fed into the boilers. Mercury oxidation through this bromine addition ensured mercury removal within the FGD at the plant from concentrations over 10 µg/m^3 down to below 2 µg/m^3. $CaBr_2$ was applied as KNX-Technology by Alstom/Vosteen Consulting. This high temperature bromine technology has also been applied successfully at the Pleasant Prairie Plant (2 x 600 MWe) in Wisconsin (Vosteen and others, 2012) and at numerous waste incineration plants in Germany and France (Vosteen, 2016).

Lignite is usually a challenge for mercury control because of the low inherent mercury oxidation rate. However, successful mercury control was demonstrated at Great River Energy's 2 x 600 MW lignite-fired plant in North Dakota, USA, over a 30-day period in 2014. A combination of $CaBr_2$ addition to the coal feed plus the injection of 'Kleenscrub', an organic-sulphide liquid, to the FGD reaction tanks was shown to be highly effective in achieving compliance with the Mercury and Air Toxics Standard (MATS) limit with lower $CaBr_2$ requirement and lower costs than predicted for using sorbents or $CaBr_2$ alone (Larson, 2014).

Glesmann (2016) notes that, while FGD can be considered a control option for mercury, there are several caveats to be considered:

- the wet FGD system will only capture oxidised mercury;
- a scrubber additive (such as a bromine-based material) is likely to be needed to sequester the mercury in a solid form for removal;
- the solid waste may need to be separated from the gypsum (solid sorbents can be removed by cyclones);
- the effects of additives on the wet chemistry of the FGD must be evaluated and controlled to ensure the primary function of the system (sulphur removal) is retained; and
- if bromine is added then corrosion and wastewater issues must be addressed.

Many plants in the USA are making plant adjustments and retrofits to comply with the new MATS. Several plants are using activated carbons and sorbents and switching to baghouses to maximise mercury capture. Oxidants are used to a lesser extent. The EU is about to update emission limits under the Industrial Emissions Directive (IED) and will, for the first time, include limits for mercury, at somewhere between 1 and 4 µg/m^3 for hard coal and 1–7 µg/m^3 for lignite, depending on plant size and age. In advance of this, the EPPSA (European Power Plant Suppliers Association, 2015) has estimated costs for mercury reduction at a theoretical, typical, 800 MW plant, typically with an ESP system, with 0.2 mg/kg mercury in the coal. For an approach based on oxidant (bromine addition) the cost is estimated as follows:

- cost for additive feed system and integration of this into the distributed control system – €400,000; and
- cost for reagent, assuming 30 kg/h bromine reagent is around 100 €/h, giving €750,000 for a plant operating for 7500 hours per year.

There is a question of potential corrosion issues with the use of bromine and in most cases it appears that the effect is either minimal or can be controlled. The effectiveness and therefore the ultimate cost of bromine addition will depend on coal and plant characteristics with the oxidative effect of SCR systems helping to lower oxidant requirements by up to a factor of 10 (EPPSA, 2015).

2.4.2 Enhancing mercury capture in existing systems with sorbents

Activated carbon and related sorbents can be injected into the flue gas to help capture oxidised mercury in the particulate form in existing particulate control systems. The cost of sorbent varies from 1.5–2 €/kg, depending on the type of sorbent. For the typical plant in the EU, as discussed above, the requirement would be 100–400 kg/h leading to costs of €850,000–3,400,000 for 7500 hours per year, excluding any additional operation and maintenance costs. This is significantly more than the cost of oxidant injection, as discussed above. As sorbents improve over time, material quantities are dropping, with some plants requiring <22 kg/h (Glesmann, 2016).

For a plant with FGD in place, mercury removal may occur as a 'free' co-benefit effect. However, re-emission from the scrubber fluid is common and therefore additives may be required to control this, which is an additional cost. EPPSA (2016) quotes a cost of around €500,000 for an activated carbon dosing station to reduce re-emission. New scrubber additives are also increasingly being used to reduce the re-emission of mercury from wet FGD systems. For example, Nalco produces MerControl 8034 for such a purpose (Maier, 2016) and PRAVO®200 from Vosteen Consulting applied from 2016 at Unit 2 of Stadtwerke Munich Plant (350 MWe) (Vosteen, 2016).

For some plants the existing pollution control system may be adequate for sorbent injection. As discussed earlier, this is more the case for baghouses than for ESP. In other plants, a move from ESP to baghouse or the addition of an extra baghouse downstream of the existing control system may be necessary. The EPPSA cost estimates for various control options for mercury at plants in the EU are summarised in Table 6.

Table 6 Estimated costs for mercury control options at plants in the EU (EPPSA, 2016)

Technique	Fuel Cl content	Oxidant	Separation	Treatment	Investment, €/MW	Operation, €/MW.y
SNCR + DSI + FF	Low	Br_2	ACI	None	2000	2250
	High	NA	ACI	None	1250	1500
SCR + SDA/CDS + FF/ESP	Low	Br_2	ACI	None	1500	1300 (FF) 3700 (ESP)
	Low	OXI	ACI	None	1250	1100 (FF) 3500 (FF)
	High	NA	ACI	None	1000	1000 (FF) 3400 (ESP)
SCR + ESP + WFGD (with unsaleable gypsum)	Low	Br_2	ACIW/OSW	WTP	1000	300
	Low	OXI	ACIW/OSW	WTP	850	150
	High	NA	ACIW/OSW	WTP	500	50
SCR + ESP + WFGD (with saleable gypsum)	Low	Br_2	ACIW	GPT	2000	275
	Low	OXI	ACIW	GPT	1700	125
	High	NA	ACIW	GPT	1400	30

SNCR	selective non-catalytic reduction	DSI	dry sorbent injection
FF	fabric filter/baghouse	SCR	selective catalytic reduction
SDA	spray dry absorber	CDS	circulating dry scrubber
ESP	electrostatic precipitator	GPT	gypsum pretreatment
WFGD	wet flue gas desulphurisation	OXI	oxidation catalyst
ACI	activated carbon injection	ACIW	ACI injection into wet scrubber
WTP	water treatment plant	OSW	organosulphide addition to west scrubber
WTPS	WTP with sludge concentration		

The table does not consider the move of Hg and selenium to the water phase and, if bromine is used, there is the potential for bromine by-products in the water discharge. This may require a change in water processing and separation systems. The table does not consider the costs of license fees for the use of commercial products within these estimates. Although the table contains much information, it is clear that mercury control costs are lower for those plants which have baghouses in place rather than ESP systems. Costs go down significantly if wet FGD systems are in place, although treatment of wastewater and by-products also have to be considered. Plants with low chlorine coals and no FGD in place or planned (few remaining in Europe) would have to compare the economics of using oxidants and ACI in the existing ESP system with moving to a baghouse. Although this table has been produced based on EU variables, the basic differences between costs may be applicable in other regions.

There are numerous sorbents on the market with much investment in the improvement of capture characteristics – the newer sorbents are cheaper and more effective than the original materials. An internet search for companies such as Albermarle, ADA Carbon Solutions, Nalco, Cabot and BASF will give just a small indication of the options available. For example, CABOT produces the DARCO range of sorbents and activated carbons, including sorbents which will reduce the unburnt carbon in ash and thus avoid any potential loss in fly ash sales through activated carbon use (Cabot, 2016). Nalco produces several sorbent products which are applied at full scale at several plants in the USA. One of these is an un-named coal-fired 580 MW thermal electric supercritical boiler equipped with low NOx burners, SCR, spray dry absorbers

(SDA) for SO_2 control, and a pulse-jet fabric filter (FF) for particulate control. The plant fires Powder River Basin (PRB) coal. Using advanced sorbent (MerControl 7895) meant that less sorbent was required. MerControl 7895 was applied to the coal at a concentration of 25 ppm. This reduced mercury compliance costs for the plant by over US$1.1 million per year (Maier, 2016).

2.4.3 Combining multiple systems

Using several control technologies in sequence not only ensures the capture of multiple pollutants (particulates, SO_2 and NOx) but can also enhance the potential co-benefit effects to reduce mercury as well as reducing overall emissions further.

Shumin (2015) highlights the fact that, to achieve near-zero emissions (for example, below 5 mg/m^3 particulate matter) multiple technologies must be applied. For the Shenhua group in China, this means traditional ESP (dry) or baghouse plus synergistic particulate removal in an FGD system and also a WESP. This provides a series of capture systems for the particulate matter in the flue gas:

- the initial ESP or baghouse will capture 99.8–99.9% of the particulate matter leaving the combustion zone. This should pull particulate emissions down to below 20 mg/m^3;
- an FGD system (wet) will then remove a further 50% of the particulates remaining in the flue gas, although some new gypsum droplets will be entrained into the flue gas. This means that the particulate concentration leaving the FGD should be around 10–15 mg/m^3;
- a WESP system will have a particulate removal efficiency of >70% bringing the final particulate emissions from the stack to below 5 mg/m^3; and
- if the FGD tower is equipped with a high efficiency demister then particulate removal in the FGD could reach 80%, bringing the emissions down below 5 mg/m^3 without the need for a WESP. However, WESP systems tend to give more effective control than high efficiency demisters.

To achieve ultra-low sulphur emissions, plants can use a combination of low sulphur coals and FGD systems. Similarly, the combination of low NOx burners and SCR systems at Shenhua's plants in China achieve NOx emissions below 20-40 mg/m^3, lower than the limit for gas turbines in China (Shumin, 2015).

2.5 Working through a retrofit selection process

All flue gas control systems, whether they have been designed for particulate, sulphate or nitrate control, have an ability to capture other pollutants simultaneously. However, the extent of this effect is case specific, depending on coal type, plant configuration and other conditions. It is therefore still the case that the majority of plants will look to install particulate, SOx and NOx control systems individually, in series, as required. The plants will then try to enhance the performance of these existing systems, through minor modifications, oxidant or sorbent addition, to maximise co-benefit effects to achieve as much reduction in emissions of as many pollutants as possible. This will require some expert advice from commercial companies and equipment suppliers on how best to optimise control performance. In some instances, the existing systems will simply not be up to the job of enhanced pollution control to comply with tightening emission limits and replacement or retrofitting of additional new systems will be required.

The previous sections included, where possible, an idea of the technical factors used to determine the most appropriate control technology for each pollutant based on coal type, existing plant configuration and other plant-specific factors. However, there is a more general process each plant must follow to determine how a project will proceed. Johansson (2012) summarises the selection process for FGD technologies in Figure 5, but the process is equally applicable to the selection process for most other flue gas cleaning systems.

Figure 5 Selecting control technologies (Johansson, 2012)

Economics is usually by far the most important consideration. There has to be a balance between what has to be achieved, in terms of emission reduction, and what is affordable. In the worst case scenario, older, less commercially viable plants may find that investment in flue gas control is simply too expensive to be justified, bearing in mind the limited remaining lifetime of the plant. In situations where the plant is still required as a power source to the grid, there may be some derogation allowed to ensure that the plant can continue running for a limited period of time (such as a total number of hours, as under EU regulations) to continue to provide power to the grid until a new source of power can be found as a replacement (Nalbandian, 2015).

If the plant decides to move forward with control technologies, then price is often the main criterion. The balance of capital costs versus operating costs must be found. For example, low NOx burners may be costly to install but, once in place, there are no further operating costs or consumables to be purchased. SNCR systems may appear to be cheaper than SCR systems but have similar or higher operating costs and may have ammonia slip issues. The decision on sulphur control may take into account the by-product situation – will the process produce a marketable product which can bring in revenue or create a new waste stream with added cost?

Forward thinking plant managers may consider the likelihood of new emission limits based on knowledge of potential impending legislation. For example, although the new Minamata Convention on mercury has not yet been ratified, it is clear that it is likely to lead to tightening emission limits for mercury emissions from new and existing plants in many countries in the future. And so some plants may be more likely to look at potentially more advanced multi-pollutant systems (*see* Chapter 3). However, many plants will continue to install control technologies as and when required in a piecemeal manner. The approach is very dependent on individual manager or operating company choices.

Technical considerations will include the control efficiency of the technology and whether it is adequate for the job. For example, the emission limit set will determine whether low NOx burners are adequate or whether further spending is required for an SCR system. So Some plants may also have space issues – if the site format is challenging, then the cost of retrofitting an FGD on an older unit can be more expensive than installing an FGD on a new unit. WESP systems appear to be increasing in favour in China where they can be retrofitted onto existing units, in addition to any existing ESP systems, in a horizontal format, reducing space constraint issues.

Finally, once a decision has been made on which technology is required, the operator can then turn to the market to see what is available, comparing costs and services from the different suppliers.

2.6 Comments

Control technologies such as those for particulates, SO_2 and NOx are well established. They have been on the market for decades and are designed to ensure that power plants comply with current legislation. The decision on which technology to use is based on factors such as the amount of pollution reduction required, the coal chemistry, the existing plant configuration, and installation and running costs. A purchase will not normally be made until a significant amount of testing and modelling has been performed. As the global market has grown, prices in most regions have dropped as the technologies are mass produced.

The market for most standard control technologies as new retrofits in North America and the EU is tailing off as most plants have had some form of control installed. A market still exists for maintenance and upgrading and for replacement and repair. However, as emission standards continue to tighten, and new countries follow in setting emission limits, the global market for these technologies remains strong and, in Asia, continues to grow.

There is also an emerging market for combined flue gas control. Many control technologies have co-benefit effects, reducing emissions of several pollutants, including mercury, simultaneously. And so plants are having to adjust existing or new systems to maximise co-benefit reduction or, where this is insufficient, they must install newer, more advanced control systems. Some plants can use oxidants and/or sorbent injection, making the most of the systems already in place, such as particulate, SO_2 and NOx controls, to reduce costs and installation issues. However, for other plants, with older systems or systems less compatible with sorbent and oxidant use, there may be the need to move from ESP to baghouses or WESP. As has been seen in the USA and China, tightening emission limits for fine particulates and mercury often require the upgrading of existing particulate control systems and there appears to be a global trend towards baghouses over ESP for this purpose. Where these options are insufficient to comply with tightening emission standards, additional multi-pollutant control systems, or flue-gas 'polishing' systems, may be required. These are discussed more in Chapter 3.

3 Multi-pollutant control and emerging technologies

As mentioned in Chapter 2, the definition of a multi-pollutant control system is confusing as all pollution control systems offer the potential to reduce several pollutants simultaneously. However, many new systems are emerging into the market place which are commercially defined as multi-pollutant control systems. Although the implication is that these systems could combine individual particulate, SO_2 and NOx control systems into one single unit, this does not yet seem to be happening. Instead, most multi-pollutant systems currently on the market appear to be being sold with the intention that they be used in addition to the usual fleet of flue gas control systems as downstream polishing systems to further clean the flue gas to meet tightening emission limits. And so, although in future single multi-pollutant control systems may be sold to be fitted onto new plants, the vast majority of the current market remains steady in the deployment of individual control technologies for particulates, SO_2 and NOx in series with the addition of multi-pollutant control technologies to the end of this chain to meet increasingly stringent regulations.

There are a few systems emerging to upgrade boilers to improve efficiency and reduce emissions. One advanced option is the Clean Combustion System from CastleLight Energy which replaces pulverised boilers with a hybrid of coal gasification and combustion (CastleLight, 2017). Whilst effectively reducing emissions, this is a significant change to plant operation rather than a retrofit emission control system and, as such, is outside the scope of this report.

3.1 Emerging new technologies

A recent report from the IEA CCC (Zhang, 2016) reviews methods for reducing fine particulates from coal combustion. Table 7 gives some examples of the multi-pollutant control technologies available in the current market and the extent to which they are commercialised. The table is by no means comprehensive, but rather gives examples of the types of systems already available and emerging into the marketplace. More details of each of these processes can be found in complementary IEA CCC reports (Zhang, 2016; Sloss 2012, 2015a; Carpenter, 2013).

Table 7 Multi-pollutant control technologies			
System	**Format**	**Demonstration status**	**Marketed by**
WESP	Wet ESP	Full scale at many plants	Various
COHPAC™	ESP plus fabric filter or pulse-jet fabric filter	1700 MW installed on coal plant and waste to energy incinerators	EPRI, via Babcock and Wilcox, Hamon Research-Cottrell
TOXECON™	Sorbent, and pulsed-jet fabric filter (COHPAC plus sorbent)	Fitted in 8 plants in USA	EPRI, via Babcock and Wilcox, Hamon Research-Cottrell
EFIC, electrostatic fabric integrated collector	Similar to COPAC with pulse-jet fabric filter	50 units currently in operation	China Fujian Longking
ESFF, ESP-FF hybrid system	Split level filters either integrated or separated	3 plants in China and 1 in India	Zheijian Feida Environmental Science and Technology Co
ECO™ Technology	Dielectric barrier discharge, ammonia based scrubber, and WESP	Slip-stream demonstration	Powerspan
ReACT™	Regenerative activated coke technology	Full scale – Isogo, Japan; Weston, USA; industrial plants in Germany	J-Power, Haldor Topsoe
SNOX™	Dry catalyst/reactors with ammonia addition	Full scale, Nordjyllandsvaerket, Denmark, plus industrial sites	Haldor Topsoe
SNRB™ (SOX-NOx-Rox-Box)	Alkali sorbent injection and high temperature fabric filter	Demonstration	Babcock and Wilcox
Airborne™ Process	Sodium bicarbonate injection with wet sodium scrubbing and oxidation	Pilot and small scale	Airborne Clean Energy
Neustream™ Technology	Dual-alkali FGD with upstream ozone injection	Pilot scale	Neumann Systems Group
Gore mercury and SO_2 control modules	Passive, modular, fixed absorption media modules	2100 MW installed in coal-fired power plants in the USA and demonstration pilots in European plants	Gore
Skymine™ Process	Electrochemical sodium hydroxide scrubbing	Pilot scale	Skyonic Corporation
Tri-Mer™	Modular ceramic catalyst and oxidant units	Pilot scale	Tri-Mer

Although there are many more companies than those listed in the table working on mercury control option, only a few of these systems have made it to full-scale demonstration stage.

It is interesting to note the difference in scale of systems developed in China versus those developed in the USA – although the Chinese EFIC system appears to be functionally similar to the US COHPAC system, the EFIC system has been installed at over 50 plants whereas the COHPAC system has only been installed at a handful of units. This probably reflects the significantly larger market in China which offers greater sales and therefore a faster movement into more affordable mass production. WESP systems, discussed in Chapter 2, are becoming relatively common in China as flue-gas polishing systems to enhance fine particulate and mercury control.

COHPAC is marketed in the USA by the Hamon Group (Hamon, 2016) who work closely with EPRI (Electric Power Research Institute). They report that the COHPAC system has been demonstrated on full-scale plants up to 600 MW, with advantages over standardised particulate control systems including:

- experience on coal applications up to 600 MW;
- fewer filter bags compared to a fabric filter;
- highly compact footprint;
- lower overall capital cost;
- meets stringent emission standards;
- multi-pollutant control capability (enhanced particulate capture and enhanced fly ash capture of mercury, especially if activated carbon is used); and
- appropriate for rebuild and upgrade.

Whilst acting as a multi-pollutant control system, capturing mercury and fine particulates, the COHPAC and EFIC systems are primarily particulate control devices with added benefits and will be purchased as such.

The ReACT system mentioned in the table above has been running for several years at J-POWER's Isogo plant in Yokohama, Japan. The plant burns low sulphur coal and incorporates high-efficiency ultrasupercritical boilers, low NOx burners and controls, primary SCR and ESP and uses the ReACT system as a flue gas polishing technique. The system has been in operation since 2002 and demonstrates excellent emissions control (Peters, 2010):

- less than 5 ppm of SO_2 at the stack with an SO_2 inlet concentration of 200 ppm–400 ppm. SOx removal efficiency is over 98%;
- greater than 90% mercury removal;
- an additional 20–40% NOx reduction provided by ReACT as a co-benefit, dropping stack NOx concentrations to <10 ppm. An SCR is installed upstream as the primary NOx control; and
- minimal water requirement.

The ReACT system, marketed by Haldor Topsoe, is also being applied at the Weston plant in Wisconsin in the USA.

The SNOX system, also marketed by Haldor Topsoe (HT, 2016), is primarily a flue gas desulphurisation system which includes the following steps:

- dust removal (this is only residual dust removal in the catalyst, the dust is removed upstream in an ESP or fabric filter system);
- catalytic reduction of NOx by adding NH_3 to the gas upstream of the SCR DeNOx reactor;
- catalytic oxidation of SO_2 to SO_3 in the oxidation reactor; and
- cooling of the gas to about 100°C whereby the H_2SO_4 condenses and can be withdrawn as a concentrated sulphuric acid product.

The system has the advantage over FGD and SCR/SNCR systems in that the combined system takes up less space than these systems individually in series. The sale of sulphuric acid as a by-product will also offset installation and running costs. The system has been demonstrated at the Nordjyllandsværket coal-fired combined heat and power plant in Vodskov, Denmark, operated by Vattenfall. The power plant consists of three coal turbines and a gas turbine. No other commercial examples of the SNOX system on coal-fired power plants have been found in the literature.

The GORE Mercury and SO_2 Control System (GMCS) is a fixed sorbent system based on discrete stackable modules that are installed downstream of a particulate collection system. The modules are designed with a unique open channel structure as shown in Figure 6.

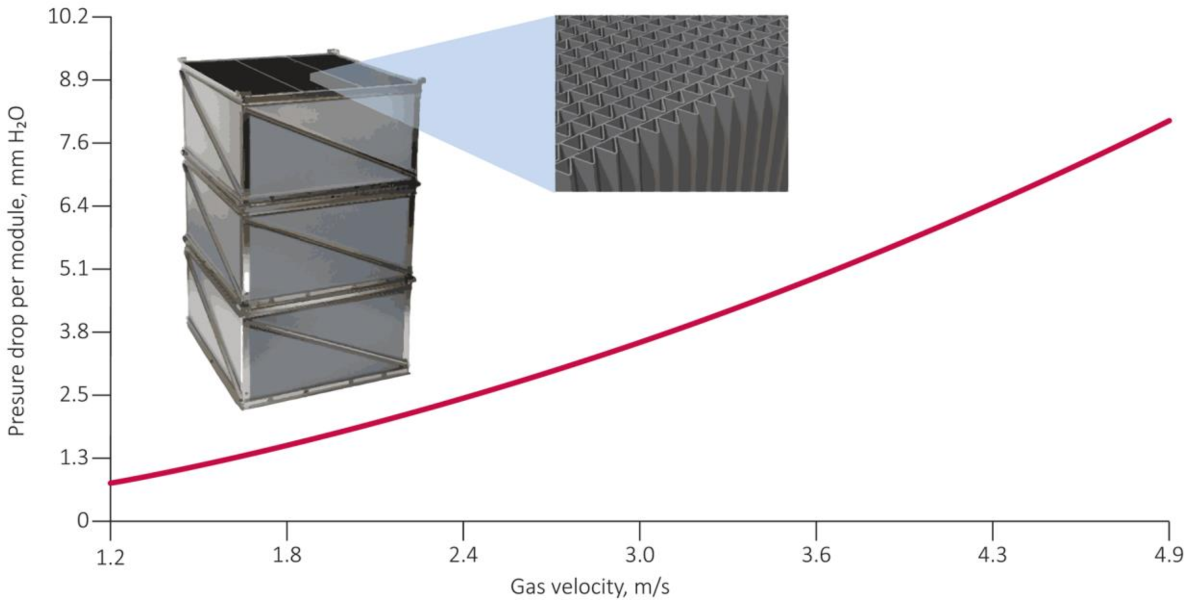

Figure 6 Gore modular fixed sorbent system (Gore, 2016)

The GORE system shown in Figure 6 contains a catalyst (in addition to mercury adsorption and sequestration chemicals) to promote oxidation of mercury but also of SO_2 into H_2SO_4 which can be captured separately. The combined system therefore provides both SO_2 and Hg control without the need for any injection of oxidant and does not produce any materials which then have to be captured in existing particulate control systems. Rather the sorbent units themselves can be replaced when necessary. The system has been used in several coal and sludge incineration plants in the USA (First Energy, Ft Martin, AEP; AES Cayuga; and AEP Conesville) and is also being tested at pilot scale by SBB in Poland, with the view to fitting a full-scale system at the Patnow II plant. Further demonstration pilot units are being installed in German lignite-fired power plants (Zmuda, 2016; Kolde, 2016).

The system produced by Tri-mer (2016) in the USA is also produced in a modular format and is designed so that the plant operator can select the individual parts of the process separately to ensure the capture of the pollutants required, as shown in Figure 7. This is simply an advanced version of particulate, SO_2 and NOx control systems in series, but in a more modular, controllable and potentially compact manner. Ceramic filters are more expensive than ESP or baghouses for particulate control. However, the multi-pollutant control capabilities of such a system could mean that overall costs are actually lower. For the moment, there do not seem to be any full-scale demonstrations of the Tri-Mer system on coal-fired power plants.

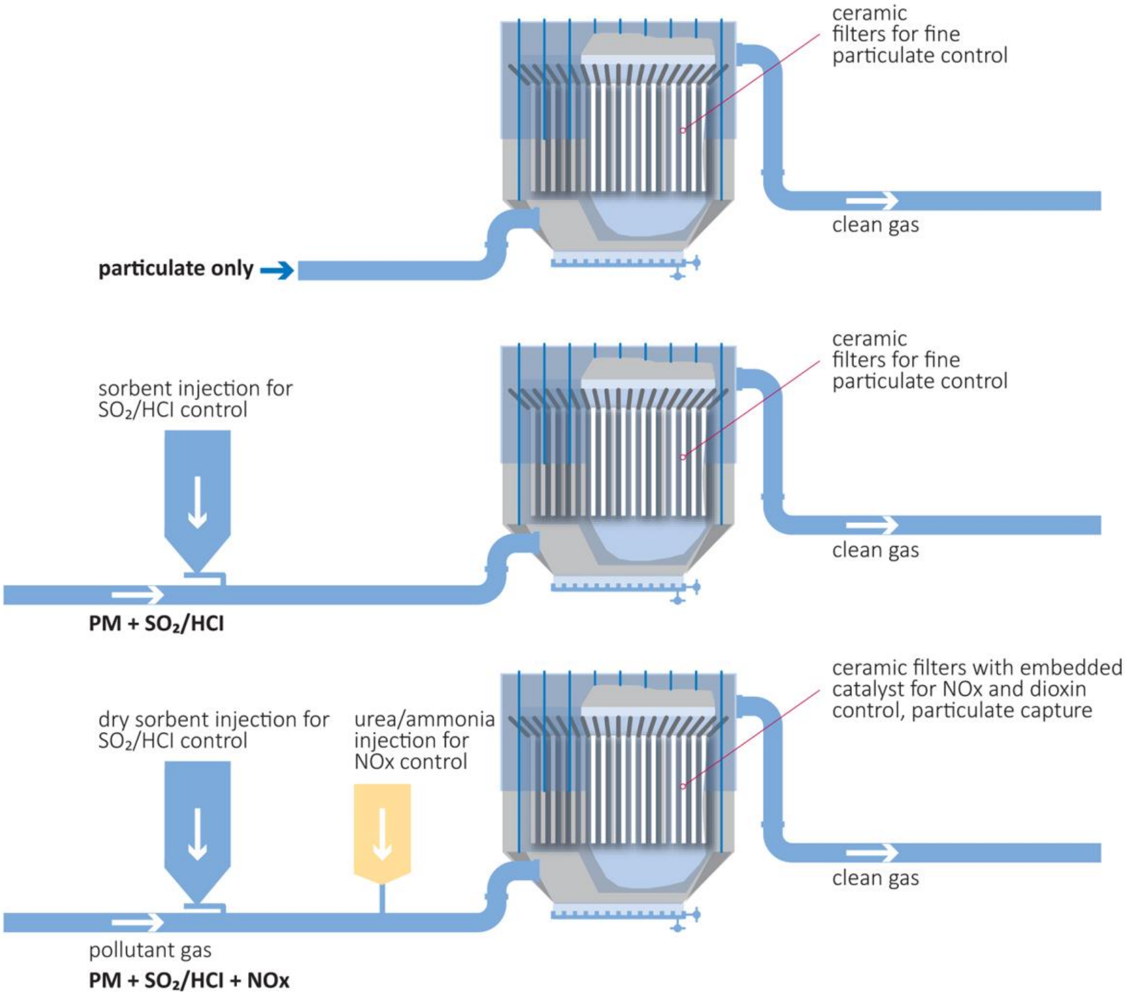

Figure 7 Tri-mer options for multi-pollutant control (Tri-mer, 2016)

The interested reader is recommended to search the internet for more timely information on the technologies summarised in Table 7 as it is not possible for this report to give a fair representation of the current status of such technologies since some are still moving into the marketplace. Further, new technologies may be under development which have not been included in this report. This is an indication of the continuing requirement for advances in flue gas control systems to meet tightening emission limits and to meet the unique requirements of new markets in emerging regions (*see* Chapter 5).

3.2 Selection criteria

The selection process discussed in Chapter 2 works for individual pollutant control systems. When it comes to multi-pollutant systems, the decision making process is different. Many of the systems in the market are relatively new and so none has yet proven more appropriate than any other. Further, the variation in coal chemistry and plant configurations along with the variation of capture efficiency for each of the pollutants by the various technologies leads to a considerable and complex matrix of potential options for any buyer. It would seem, however, that most commercial manufacturers are willing to work through these issues with plant managers; modelling, testing and demonstrating at pilot scale to determine whether a system is indeed suitable before any major purchase is made.

At the moment, the decision for multi-pollutant control is complex. Some forward thinking plants in China, the USA and Japan have acted as demonstration sites for new technologies such as combined particulate systems (COHPAC, EFIC) or sorbent- and catalyst- based systems (GORE, ReACT). However, for most of them, there is more to be done before they are regarded as standard, off-the-shelf, systems. This may well change in the future as countries such as those in Southeast Asia make technology leaps from little or no controls to control of all emissions simultaneously. Such a leap may occur soon in India, where the majority of plants do not have SO_2 or NOx control, and where new emission standards will soon require emission controls (*see* Chapter 4). However, even in India, the current discussion is focused largely on standard pollution control systems, such as FGD and SCR, with no indication of how open the market may be to more advanced, multi-pollutant systems.

Since fine particulate control is effectively enhancement of PM, SO_2 and NOx control, the selection criteria to determine the best option for fine particulate control is ultimately either advanced individual systems for each of these primary pollutants or a multi-pollutant system which has the ability to capture all simultaneously. Although some commercial systems, such as those listed in Table 7, may report high capture efficiencies, many will still show variations in efficacy depending on coal chemistry and other plant specific factors. This is why pilot- and demonstration-scale projects continue to be necessary.

Mercury chemistry is also coal dependent, and this will have a major effect on the determination of which control system is best suited on a case-by-case basis. Hutson (2016) summarises the choices for mercury control based on coal type:

Lower sulphur-containing subbituminous coals and lignites

- brominated activated carbon (ACI) give good performance at very modest injection rates;
- bromide additive plus separate activated carbon; and
- bromide additive plus SO_2 scrubber (FGD, may require scrubber additives).

Higher sulphur-containing bituminous coals

- may give good performance with SCR-FGD co-benefit, may require scrubber additives;
- ACI plus SO_3 mitigation; and
- may be the most challenging cases.

Higher sulphur-containing lignites are found in Germany and neighbouring regions which have their own challenges. These European lignites can also be higher in moisture and salts and thus differ from US lignites.

This is one reason why the control methods used to reduce emissions of mercury from lignite plants in the USA may not be as appropriate for lignite plants in Europe (Vosteen, 2016).

The United Nations Environment Programme's (UNEP) Coal Partnership, led by the IEA CCC, has developed a flow chart for determining options for mercury control based on plant configuration, as shown in Figure 8.

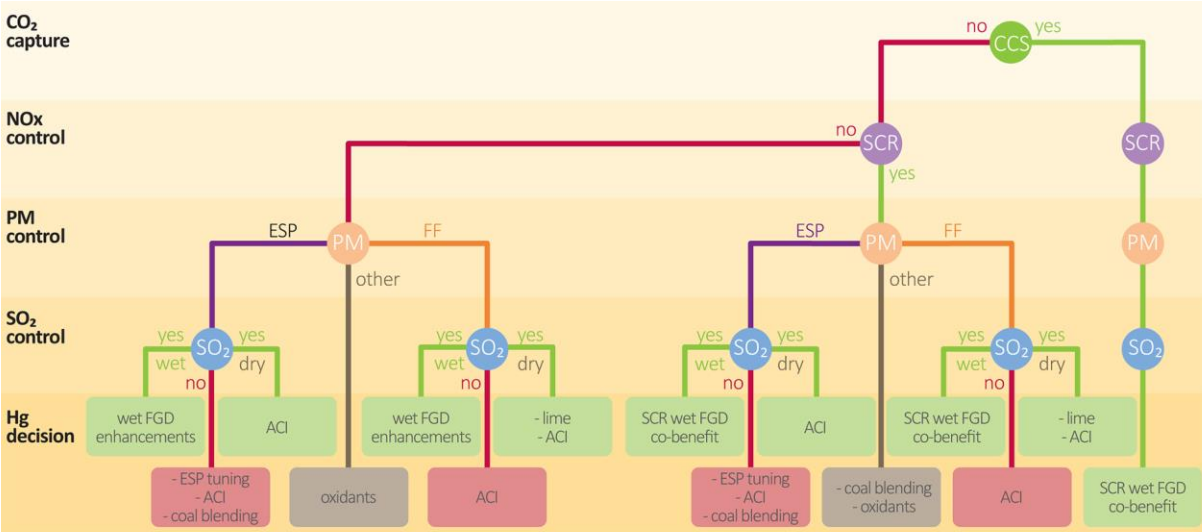

Figure 8 Decision tree for mercury control

The chart gives a general overview of the choices available for mercury control on a plant-by-plant basis. By working through the chart from the top down, the user can consider plant specific factors and narrow down potential options for mercury control systems. The flow chart is intended to be used in conjunction with more detailed guidance in the form of a best available technology (BAT) document produced by the Coal Partnership under the new UNEP Minamata Convention on Mercury. The Partnership has also produced a free, downloadable tool for estimating mercury emissions from a coal-fired plant based on the plant configuration and coal characteristics. The model, named the iPOG (interactive process optimisation guidance), is based on actual plant data from around the world, and can also be used to 'test' which potential options for mercury control (such as adding FGD, oxidant, or ACI) might be most useful as a mercury reduction plan. A screen capture of the system is shown in Figure 9.

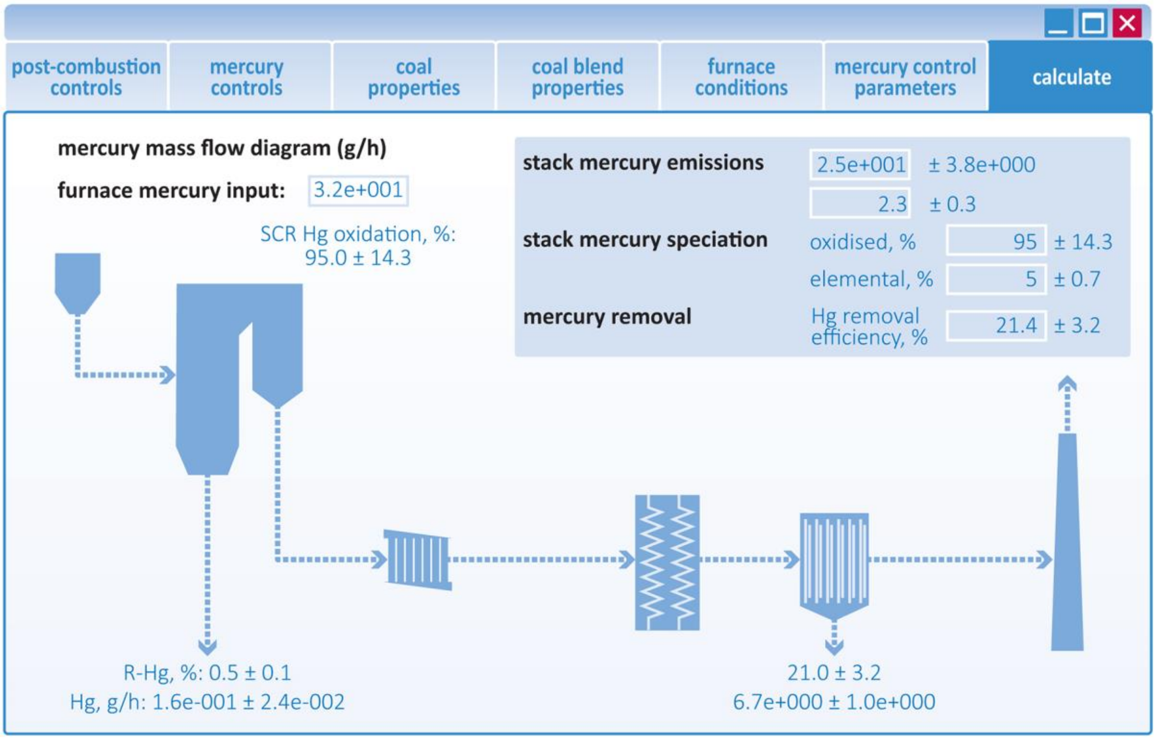

Figure 9 Screen capture from the iPOG calculation programme

The tool is simple to use and allows the operator to work through a menu to install as much or as little data as is available. Users can input coal specific data, such as ash and chlorine content, or simply select a coal most similar to that which they use. The user then selects which control systems are already in place on the plant. The calculate function then estimates, based on actual data from hundreds of plants in the USA, South Africa, India and China, the likely emissions of mercury from the plant. By going back through the selection process, the operator can then 'play' with the system to determine what would happen should certain changes be made, such as the blending of coals, the addition of oxidant or the conversion of an ESP to a baghouse system.

Although the iPOG is based on real plant data from many countries, it is not truly comprehensive as it has limited data from high ash coals and few data from European lignites. However, the iPOG is being updated by UNEP to increase its applicability.

Whilst the iPOG system is not intended to be a prescriptive means of selecting a plant mercury reduction strategy, it does allow the user to have a better understanding of the options which are most likely to be relevant in each specific case. The iPOG programme has proved to be an extremely useful learning tool during the work towards the ratification of the Minamata Convention on Mercury. The iPOG is available on the mercury page of the IEA CCC website http://iea-coal.org/site/2010/conferences/mec?LanguageId=0.

3.3 Comments

Multi-pollutant technologies offer the advantage of combining the effectiveness of several technologies into one single unit. This might imply that they are most useful in plants where there are no existing control systems. However, the majority of multi-pollutant control systems currently being installed are used as flue gas polishing systems. They are applied within a series of existing flue gas control systems to enhance control so as to achieve compliance with tightening emission limits. It is far more cost-effective for a plant manager to work with the systems already in place than to remove these and replace them with a new system. For example, a plant with a particulate control system in place and a new requirement for SO_2 control is likely to simply retrofit an FGD system downstream of the existing particulate control system rather than remove the existing particulate control device and replace it with a multi-pollutant control system unless there is some other, legal or financial, incentive.

Capital investment for a multi-pollutant control system is generally lower than for a combination of individual systems but only if multi-pollutant control is actually required. Some multi-pollutant control systems rely on by-product sales to be economically competitive as retrofit technologies. However, many will also often offer a flexible modular format, a smaller footprint, and a shorter installation time and are therefore easier to install than a combination of technologies.

Although there are many emerging technologies, it is likely that only a few of these will reach any significant international commercial position in the market. The success of any new technology will be determined by the market requirements. At the moment, the majority of plants can achieve the required emission reductions using a combination of established technologies. And, although new technologies may have better multi-pollutant control, established technologies currently have the advantage of being just that – established. However, the more these new technologies are used, the more reliable and affordable they will become. Chapter 4 looks at the issues that established and new technologies face to enable their spread into a new international market place.

4 General factors affecting technology selection

The previous chapter summarised the selection of control technologies based simply on factors such as performance, cost, and reduction specifications. As such, Chapters 2 and 3 were written largely from the point of view of a plant manager or operator who is making a decision on which technology is most appropriate for a certain plant. This chapter looks at the bigger picture – the other factors that will affect which technology is most suitable in each application and is more focused on considerations that will perhaps be of interest to equipment manufacturers looking to break into new markets.

4.1 Existing and impending legislation

As noted in the report by the International Trade Administration (ITA, 2016), 'environmental technologies develop in settings where the cost of non-compliance with environmental rules exceeds that of compliance' – that is, coal-fired plant operators will only move to install control technologies when the cost of such technologies is lower than the costs of fines or restrictions on operation to exceed emission limits. In simple terms – strong markets for emissions control technology will only emerge in regions where coal-fired plants are legally obliged to install them.

Emission limits for pollutants from coal combustion have been covered in several previous IEA CCC reports (Sloss, 2009, 2012) and a database of emission standards is available on the IEA CCC website. A more recent report from the IEA CCC (Nalbandian-Sugden, 2016) looks at the effects of regulations and legislation on coal power production and coal demand and the interested reader is referred to this document for more detail. Simply put – the tighter the legislation, the greater the requirement for emissions control technologies. However, tightening legislation can have a negative effect on the pollution control market in some cases. For example, legislation in North America and the EU has reached a point where many older plants simply cannot afford to install the required control technologies and remain economically viable. In the EU the Industrial Emissions Directive (IED) includes emission limits and a BAT requirement which effectively requires particulate, SO_2 and NOx emissions control on all plants. Combined with the remnants of the Large Combustion Plant Directive (LCPD), the National Emission Ceilings Directive (NECD) and other national pollution control targets within member states, the IED effectively means that any coal-fired plants which wish to continue to operate into the next decade must have an ESP or baghouse, an FGD system and a NOx control system in place. Whilst the market may see this as sales to all remaining plants, this is not the case. In Germany alone, 6 GW of coal-fired capacity will have closed between 2013 and 2017 (Nalbandian-Sugden, 2016). The new MATS and CPP (Clean Power Plan) is already reported to be causing the closure of plants in the USA, with coal-fired capacity falling from 313 GW in 2008 to 280 GW in 2016 and expected to drop another 24 GW by 2025 (*see* Section 4.2). There is a balance between the cost of compliance and the potential for the return on this investment. This is discussed more in Section 3.2.

China has increasingly stringent emission limits, now surpassing the EU in terms of the control required for compliance. Figure 10 shows a comparison of current and proposed emission limits in the EU and China (Boren, 2015).

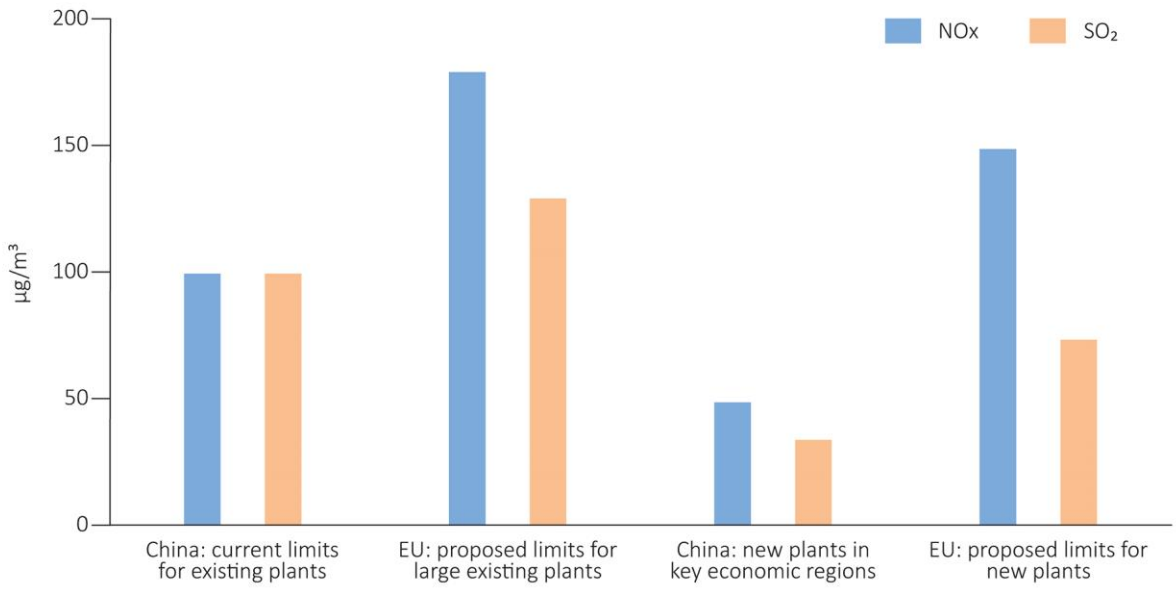

Figure 10 Emission limits, current and proposed, for China and the EU (Boren, 2015)

(Units, such as STP, not further defined in original document)

The tightening of emission limits in China is in response to the considerable air quality issues the country faces and is the force behind the rapidly growing clean coal technology market in the country (*see* also Section 4.4).

Yamamoto (2010) gives an interesting and valid view on environmental standards in emerging regions, suggesting that environmental standards being set in some regions of Southeast Asia are too strict, considering the technical and financial conditions. Environmental standards need to be based on technical and financial feasibility. Where technologies to reduce emissions are costly, low interest loans and technical assistance need to be implemented with 'sufficient and realistic enforcement'. If the financial penalty for exceeding emission limits is low, then some companies will simply find it easier to pay the fine and continue to pollute. Higher fines may force some plants into compliance but, in some instances, may force plant closure or even alternative approaches such as bribery to facilitate avoidance of fees.

Kwaja and others (2012) note that many south Asian states sign international treaties and conventions on emissions reduction and pollution control and establish organisational authorities for their implementation. However, the implementation is a significant challenge due to the lack of financial and technical support, lack of co-ordination, inefficient legal and regulatory framework, no access to relevant databases, and lack of awareness amongst local populations. Kwaja and others (2012) describe the task as 'daunting' since competitive forces and national interests often trump environmental concerns and collaboration. Regional institutions comprising forums for engagement at all levels will be required to facilitate knowledge dissemination and promote technology transfer in a way that is non-competitive and effective. If emerging regions are to apply emission limits and controls, then they must be provided with assistance in terms of help with the administrative and financial burdens this brings.

In some conventions and international treaties there is leeway defined within the text to allow for economic issues. For example, the Convention on Long-range Trans-Boundary Air Pollution (LRTAP) specifies the use of control measures for pollution control but does so by requiring only the use of 'economically feasible best available technology' (Kwaja and others, 2012). Similarly, the BAT defined under the proposed guidelines for the new Minamata Convention on mercury are far less specific than for the BAT defined under more stringent regional legislation such as the EU IED. Under the IED, strict emission limit ranges are given which can be achieved using one or even a combination of technology options listed whereas the Minamata Convention specifies no emission limit or reduction target. Under the Minamata Convention, countries will prepare a national action plan to 'control and, where possible, reduce emissions of mercury' using any means available, with the options being subject to technological, geographical and economic considerations. And so, for some international treaties, the determination of emission reduction strategies is difficult to predict and commonly relies on some form of legislation emerging at the national level which is more prescriptive and legally binding.

Although much of the compliance for coal-fired power plants is forced by the legislation, many control technology manufacturers are relatively forward thinking in terms of the efficiency and control capabilities of their systems. As discussed in Chapter 2, particulate control devices are designed to reduce emissions of particulates as much as possible. Whilst many technologies are bought to meet existing and impending legislation, it is important to note that many technologies are actually designed to exceed this requirement. For example, many coal-fired units in the EU are fitted with particulate control systems which reduce emissions well below the required emission limits. Whilst this is done largely for compliance, sometimes for plant permits which are tighter than the national or regional emission limits, many plant managers appreciate the value of installing equipment which exceeds requirements and demonstrates social responsibility. As shown in Figure 11, new HELE (high efficiency low emission) plants are being designed and built which are significantly cleaner than the current average plant. This social responsibility is a strong factor in Japan, where plant managers pride themselves on having the cleanest plant possible. China also seems to be stepping up to demonstrate that it can produce and operate plants which are as clean as achievable, with newer plants actually having lower emissions than gas-fired units (*see* Chapter 4).

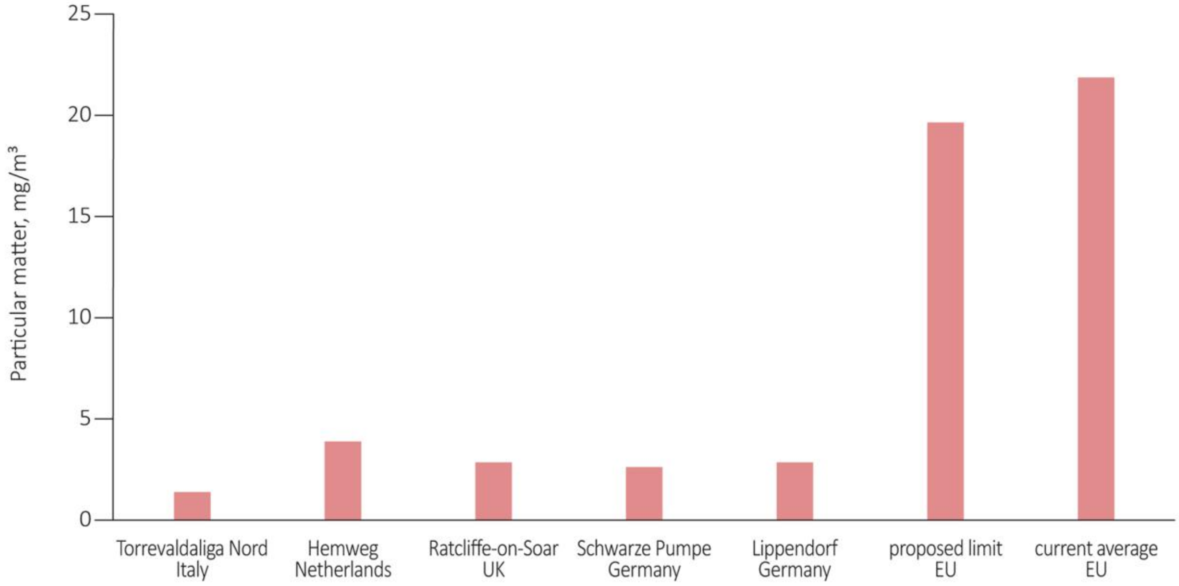

Figure 11 Particulate emissions from plants compared with legislated emission limits (Boren, 2015)
(Units, such as STP, not further defined in original document, primary particles only)

Figure 11 shows that several plants in the UK and Germany have installed state-of-the-art control systems which achieve emission levels almost an order of magnitude lower than that required by the legislation. And so, although some emerging countries lag in their move towards installing control technologies, these technologies continue to improve through their extensive deployment in western economies. Once they do move into the emerging market, they are arguably proven, reliable and more affordable. This should facilitate a more efficient technology leap in countries which move towards emissions control in the future.

4.2 Plant age issues

Most legislation on coal-fired power plant emissions will vary depending on factors such as coal type and plant size. Much of the legislation will also vary with plant age; emissions limits are generally more lenient for older units.

For most existing plants, space is at a premium. Plants have been designed to use the available space efficiently and therefore do not often have empty space within the plant boundaries for new technologies to be retrofitted several years later. This will, of course, affect which technologies can be applied on a case-by-case basis. If a retrofit system has to be modified to fit in a constrained area, then this is likely to add to the cost.

Existing plants may have a limited footprint and retrofitted systems will need to work around what is already in place. In some situations, there is potential for the re-use of existing systems – stack space can be used for additional processing or cycling. However, an important consideration for retrofitting is the loss of revenue during any periods of closure. In situations where power supply is at a premium, retrofitting options may favour off the shelf, modular systems which can be installed quickly.

However, as discussed earlier, many units will consider retrofitting to be uneconomic and, instead, will consider, derogation, grandfathering, mothballing, and/or ultimately, closure. The IEA CCC report by Sloss (2016) looks at the effect of the increased use of renewable energy on existing plants – the move away from coal and, conversely, the increased pressure on remaining plants to run as efficiently but as cheaply as possible to maintain electrical output to the grid when renewable energy is scarce. Plants in the UK and Germany are increasingly being told that they are to close but then they are required to remain open and on stand-by to top up the grid when necessary. For some of these plants the decision to close will have been due to the age of the plant making retrofitting additional flue gas control systems uneconomic. But, if they continue to run, then there will be increasing pressure on the plants to install control systems to comply with impending legislation in order to remain in compliance as their lifetime is extended.

4.3 Geographical/regional considerations

Plants will face regional-specific challenges. The ITA (2016) note that neither environmental needs, such as the lack of potable water, nor conservation philosophies, such as the preservation of natural resources for local communities, translate into a tangible market for environmental technologies. It can also be an issue to ensure that such factors are considered appropriately during project planning and execution. The ITA notes that resource scarcity and the corresponding demand for resource efficiency are evolving and are important drivers of environmental technology markets. This applies both to the energy sector itself as well as to the relevant control technologies and the materials required to construct and maintain these pieces of equipment. There are therefore issues that need to be evaluated and understood before moving into a new regional market. Case studies would help to share experience from those who have faced, and hopefully, overcome, these problems.

Individual countries face different environmental issues. For example, Australia does not suffer significantly from transboundary air pollution issues as it is relatively remote from other emitting regions. Conversely, countries in SE Asia, Europe, and individual states in the USA, share their air shed and must therefore work together to reduce overall emissions. Kwaja and others (2012) discuss the challenges of pollution reduction in South Asia, especially Bangladesh, India and Sri Lanka. These regions are geographically close and therefore share similar challenges. The use of technical assistance protocols has been recommended to encourage shared knowledge and experience in three areas:

- emission standards;
- implementation and legal matters regarding emission standards; and
- health and socio-economic impacts of air pollution.

Kwaja and others (2012) propose a legally-binding instrument for strengthening the framework of air pollution reduction in South Asia. This framework would include the sharing of information on monitoring, collection and analysis of air quality and emission data. Such an instrument would also need to recognise and establish differentiated national programmes to ensure that targets are achievable in the most cost-effective manner. It was noted that, for such an instrument to be effective, there would need to be capacity building and inter-state technology transfer and that supporting funds would likely need to be sourced through a sustainable financing mechanism.

Sufficient water availability is an issue in many emerging regions, resulting in the growth of investment and development of water treatment and re-use technologies. Carpenter (2015) has produced an IEA CCC report on such issues highlighting water availability and policies in China, India, the USA and South Africa and how these policies may affect the selection of coal-fired plant configurations.

4.4 Challenges for international marketing

Individual countries have developed their energy portfolios and pollution control strategies independently and, as a result, differences in standards and regulations between countries can arise which lead to difficulties in international trade. Differences in emission standards – in their requirements and the way they are applied in practice – can mean that some systems are less viable options for control in some regions. Some emission standards are measured in concentrations, some in totals over set time periods, and some as performance standards (such as reduction factors). This can mean that the approach to the sale of equipment must change to suit the market. New technologies are often developed to meet these specific, set goals. For example, systems developed in the USA have been largely designed to reduce emissions to below established emission limits, according to the national or regional requirements and formats (such as emission concentrations or totals per hour). When such a technology is to be applied elsewhere, the legislation and requirements may be different. Although most control technologies are designed to reduce emissions as much as possible, this may be based on a volume or concentration basis, a reduction factor basis or even an efficiency basis. Further, performance factors, such as concentration, and efficiency, may be influenced by regional variations in terms of standardised temperature and pressure or efficiency basis (higher or lower heating values). This means that a technology may need to be tested according to the new requirements and, in many cases, this requires a slipstream, pilot or even full-scale demonstration on site. It is not uncommon for the cost of such demonstrations to be shared or at least partially covered by the company supplying the equipment. In China for example, where standards are set at the regional or municipal level, this may mean that the demonstration stage has to be repeated several times in several locations (ITA, 2016). The ITA also note that the failure to provide mutual recognition of product and professional certifications can contribute to barriers to international sales. The differences in equipment certification and performance standards between even the EU and the USA can lead to additional fees for testing and conformity assessment to attain certifications to be able to sell into the market. China and others may require equipment certification which is only granted to local products.

Many of the systems being developed in the EU and the USA are designed to fulfil BAT and MACT (maximum achievable control technology) requirements, as defined within national legislation and guidance. However, many countries which sign-up to international reduction protocols with associated BAT or MACT requirements do so with the more lenient definition of BAT/MACT 'where economically viable'. Therefore these countries are allowed to install cheaper, potentially less effective, control technologies than those installed elsewhere.

Yamamoto (2010) notes that, due to the diversity of environmental problems, environmental management is technologically, politically and economically complicated. Further, harmonising standards and approaches through bilateral cooperation must be carried out carefully otherwise it can result in intervention in domestic affairs which can lead to other problems.

In some countries, such as the USA, the government provides help to companies moving into international sales in some sectors. This includes assistance with (ITA, 2016):

- policy dialogue and development;
- technical assistance for regulatory development and environmental management;
- direct promotion and advocacy; and
- financial vehicles for project development and project finance.

The ITA (2016) note that, in the environmental system market place, the time it takes for a company to foster a new business relationship that leads to an actual sale is anywhere between one and five years. If this is an international deal, then time and money must be invested to initiate and maintain this relationship. Most importantly, perhaps, is the consideration that export programmes, such as those in the USA, often only operate over a three-year period.

4.4.1 Funding and financing

Whilst expensive, commercially available market forecasts may consider potential sales, they do not necessarily represent 'likely' sales. Just because a plant should fit a control technology does not necessarily mean that it will or that it can. There are many reasons why a coal plant may derogate, delay or even fail to fit required control measures. Many of these issues have been discussed in previous sections but perhaps the most important issue is affordability. As noted by the ITA (2016), whilst regulatory enforcement is typically the mode of environmental market creation, finance is the means. Resources are needed to create markets for the required control technologies.

Technologies developed in countries such as the USA have a level of sophistication and material quality that makes them inherently more expensive than an equivalent piece of technology produced with inferior and/or cheaper materials elsewhere. Logically the marketplace is skewed towards lower cost alternatives, often putting more expensive imports at a disadvantage. Over and above this, preferential procurement practices may favour domestic suppliers or suppliers from aid-donor countries which can create a relatively 'unfair' market for international competition (ITA, 2016). Yamamoto (2010) notes that, although demand for pollution control technologies in developing countries is increasing, the control technologies applied are not always of the same high standard as applied in developed regions, with some plants using second hand or copied technologies which can be installed more cheaply.

In order to make control technologies affordable in emerging economies, financing and incentives are required. As mentioned earlier, many international treaties and conventions specify the use of control technologies for emission reductions but only call for the use of 'economically feasible best available technologies'. This means that areas with limited resources can install control equipment which is less costly. However, in many situations this may also mean that the technologies are less effective at actually reducing emissions than the more expensive options. International agreements designed to reduce global pollution, such as the UNFCCC (United Nations Framework Convention on Climate Change) can often include a mechanism to promote technology transfer to emerging nations and economies in transition and this is intended to ensure a level of quality and effectiveness to emission control projects. Funding can come in many forms and at many levels. For example, the Global Environment Facility (GEF) and the World Bank occasionally invest in clean coal demonstration projects, although there has been a recent trend away from funding of fossil fuels by some banks and other funding sources.

Market-based incentives are often used to promote the use of cleaner energy options. For example, EU member states and some individual states in the USA have their own renewable energy targets. Renewable systems also receive priority into the grid in Germany and Italy, and are part of quota requirements in the USA and, more recently, India. Green certificates help renewable updates in Sweden and Norway and auctions for renewable supply guarantee contracts in Brazil, Uruguay and India. All of these are entirely focused on renewable options. However, there are a few financial incentives that could be used to increase cleaner coal options. These include the financial support for projects which demonstrate investment security, market integration, cost effectiveness and promotion of innovation. Such tenders exist in Kenya and Japan. Investment support including grants, reduced rates of interest, and tax credits or exemptions are also provided in support of the promotion of innovation in the USA, Germany and France (ECE, 2016). However, whether these can be leveraged for promoting the update of emission control systems remains to be seen.

The USA and others, often provide assistance programmes and trade agreements to help promote the movement of technologies and expertise internationally. Transatlantic, transpacific and Asia Pacific partnerships and economic co-operative agreements exist to promote regional discussions and negotiations and export-import banks provide export and finance insurance (ITA, 2016).

According to the ITA (2016), tariffs "remain a substantial and limiting barrier to trade in environmental technologies". Tariffs can be as high as 21% for some products and can compound the price differential for international technologies "making US products prohibitively expensive in many markets or eroding profitability of US goods in export markets".

The Japan Environmental Public Corporation provides low interest loans for pollution control facilities at individual factories or joint facilities. The GAP (Green Aid Plan) and NEDO in Japan work together to develop and demonstrate simple desulphurisation systems for coal boilers for potential application in Thailand, China and Indonesia (Yamamoto, 2010).

Japan is an example of a country which has established environmental centres in some regions to promote advances in pollution control. The Japanese Agenda 21 has established centres in China, Thailand and Indonesia to provide technical assistance for environmental management and 'to identify appropriate environmental projects through policy dialogue'. The International Centre for Environmental Technology Transfer (ICETT) was established in 1991 to provide 4.7 billion yen (US$47 million) to transfer industrial environmental technology to developing countries (Yamamoto, 2010). JCoal has recently signed a memorandum of understanding with the Central Electricity Authority in India to focus on the production of cleaner power in the country. Upgrading of the Dadri Power plant in India has already been initiated based on Japanese expertise and technologies (Murakami, 2016).

China and Pakistan are working on joint infrastructure projects for clean energy with China providing half of the US$1 billion funding. Thailand is working with the Asian Development Bank on projects to diversify energy sources (McIlvaine, 2016). Funding and projects such as this can make a difference in the emerging energy landscape and may be the difference between a country investing in cheaper, dirtier plants or cleaner energy options.

A new report from the CCC on financing coal plants is currently under preparation by Paul Baruya and the interested reader is recommended to refer to this when it becomes available, later in 2017.

4.4.2 Import or build at home

As mentioned earlier, many countries will prefer to buy from local, often less expensive, suppliers, even if it means that the product is of a lower quality. Government tenders often exhibit open or explicit preference for domestic bidders over foreign tenders. Countries may also purchase preferentially from those which provide state aid and financial support. In China for example, State-Owned Enterprises may crowd out competitor technologies and establish a state-sponsored monopoly (ITA, 2016). The Indian Government has a 'Make in India' initiative to increase India's manufacturing as a proportion of the country's GDP. Power generation is included within this initiative (ITA, 2016).

Butler (2016) notes that, although Asia is the new growth market for energy, companies that have thrived in the EU and USA "will find themselves in static and saturated markets as margin businesses struggling to compete on price".

4.4.3 Intellectual Property issues

Technology transfer can promote technology leaps in some areas. However, making headway into a new marketplace is always a challenge. Commercialisation of a technology is a priority to those who have invested in the often expensive development of new control systems. In some cases, the technology can be licensed as intellectual property (IP) directly to an existing company or as assets to establish a new company. The way this is done will vary with the situation and depend on (IPO, 2016):

- type of technology;
- readiness for the market;
- ease of adoption;
- extent of IP protection;
- aspirations of the developer; and
- mission of the organisation.

The Intellectual Property Office (IPO) in the UK gives advice on technology transfer to China for example. The advice will include how to register the IP in the target region. It is important that the ownership of the IP is clear and available in the language of the target region to ensure that ownership is established and maintained. Most IP rights are territorial and so each must establish commercialisation options including licensing, development partnerships and company formation. Licensing can be appropriate in many regions where expertise is in place in the target region and the existing market may be difficult to penetrate. Developing a partnership with an existing company in the target region could help to further develop the technology. This may reduce revenue returns for the original developer but is likely to lead to greater market penetration (IPO, 2016).

Yamamoto (2010) suggests that obtaining patents for clean technologies is not easy in some regions and, even when demand is high, production may not be profitable, making private investment less tempting. It is in these situations that investment from overseas development agencies is important although, according to Yamamoto (2010), current incentives for this form of investment are insufficient and more needs to be done to make funding available.

According to the ITA (2016), intellectual property right infringement is still happening in China and affects many businesses that are trying to establish operations in the country. IP issues can be difficult to resolve in the international market. Perhaps the most well-known ongoing disagreement is that between Vosteen Consulting in Germany, which holds a patent on high temperature bromide addition in Europe and some other countries. The license to use this technology has been granted by Vosteen Consulting to Southern Company and via Alstom to different customers in the USA. However, the patent in the USA is still subject to legal proceedings (Vosteen, 2016).

4.5 Comments

Control technologies are expensive and installing them often requires plant downtime and loss of income. Thus, most plants will not install control technologies unless legally obliged to do so. And even then, many older plants will have to weigh up the likelihood of the return on investment. Units which are in the last few years of their planned lifetime may consider the installation of, say, an FGD system simply not worth the expense. This situation is becoming increasingly common in Europe where the emission limits for the ageing coal fleet, along with the skewing of financial incentives towards renewables, is pushing the economics of many coal plants to the point where closure is the only option. Some older plants will find the economics of retrofitting acceptable but may then face the challenge of finding space at the plant to install the additional bulk of a new flue gas cleaning system. In such situations, smaller, modular and cheaper systems may find a niche.

In many emerging economies, emission control will be further down the political agenda than economic growth in other sectors. Many will have arguably more important issues, such as resource preservation, community protection and water use restrictions which are hard to factor into plant design. And so, whilst developing nations are signing up to international agreements to reduce pollution, many are finding it a challenge to move that commitment into action at a national level. Some do not have the material resources or the skill sets to comply and require financial and technical support from the international community. Further, the definition of BAT within these areas often includes a 'where economically feasible' clause which allows some leeway in terms of using cheaper, but potentially less effective, systems. These regions would benefit immensely from international funding for demonstration projects to establish skill sets which can be shared and copied elsewhere.

Breaking into a new marketplace is a challenge which is especially hard when the major parameters of that new market place, such as need, affordability and applicability, are different to those in which the new technology has been developed. And so, although the growing requirement for emissions control in emerging economies indicates a new market for international sales, the market development in these regions will be very different from those which have grown in western economies. Many of these regions either do not have standards and certification for equipment or, if they do, they differ from those for the regions in which the technologies were developed. For example, an FGD system proven fit for use in the USA may have to undergo a new round of testing, often at the manufacturer's own expense, to prove its suitability in a new market. Further, pollution control systems which can be bought readily from manufacturers in the EU and the USA, are often produced from high quality materials which makes them expensive in the Asian market. Many plants in China and South East Asia will find it significantly cheaper to produce systems domestically than to pay to import them from abroad. Over and above this, China and India for example, are trying to promote economic growth by favouring the domestic manufacture of equipment. Tenders will often be more favourable to national bids and grants, tariffs and tax credits may also run in favour of home-grown technologies. International technology manufacturers may then rely on patents and IP to ensure that their systems still have a market in these regions. However, many will find that, although they should have a legal advantage in this situation, the reality is often different. It is therefore imperative that companies moving into new emerging markets work closely with the target region, preferably with a franchise or national base staffed with local experts, to ensure that they can feed into the new emerging market on a similar footing to local companies.

5 The international market and national case studies

This chapter gives a brief overview of the global market that is evolving for flue gas control technologies and attempts to identify regions where new markets may potentially emerge. In 2016, the ITA ranked the top environmental technology markets for USA manufacturers. When considering just air emission control technologies, from all sources, the top ten countries were ranked as follows, using a combination of variables to express the proportion of the potential market, as shown in Table 8.

Table 8 Top market results for air emission technologies (ITA, 2016)

Country	Market ranking, as defined by ITA
China	47.4
Mexico	26.2
South Korea	18.3
Turkey	17.4
Brazil	15.3
India	12.8
Saudi Arabia	10.9
Indonesia	9.9
Poland	8.6
Czech Republic	8.0

Since Table 8 includes technologies related to emissions from industrial sources as well as electricity generation it does not necessarily reflect the projected market for flue gas cleaning technologies, but it does hint at a potential market.

5.1 The international market place

Back in 2012, the McIlvaine Company estimated the global market for ESP equipment and repairs at over US$12 billion, with over half of that being in East Asia. The market for baghouses, including repairs, was only US$1 billion (Nicol, 2013). The global market for all air filters, including ESP and baghouses but also including industrial filters, is expected to exceed US$20 billion by 2021 (PRNW, 2016). As mentioned previously, China is reporting much success with ESP systems and has become a net exporter of these systems into the global market. The USA, on the other hand, appears to be moving more towards baghouses and pulse-jet cleaning systems, probably due to the increased use of sorbents for multi-pollutant control (*see* Section 2.4).

According to a commercial marketing guide summary (GVR, 2014), the global market for FGD (wet and dry) is expected to reach US$23.69 billion by 2020. New FGD system purchases amounted to US$8.14 billion in 2013 and, as many countries move to initiate or tighten emission limits, the market is considered to be strong. Of this, wet FGD has dominated, generating US$6.86 billion in 2013. The market for reagents and replacement parts for FGD is also expected to grow at a compound annual growth rate of 7.9% between 2014 and 2020. The largest FGD market will be in the Asia Pacific region increasing from US$8.52 billion in 2013 at a compound annual growth rate of 10.2% between 2014 and 2020. GVR (2014) named the major company players in this market as Alstom (now GE), Babcock and Wilcox, Siemens Energy, Thermax, Ducon Technologies, Hamon Research-Cottrell, Mitsubishi Heavy Industries and Marsulex Environmental Technologies.

The North American FGD market is estimated to reach US$4.05 billion by 2019 while the European market is expected to grow at a compound annual growth rate of 2.8% from 2013 to 2019 (Perdue, 2014).

Asia Pacific is the largest regional market place for FGD, accounting for over 50% of the total market in 2013 and this is expected to remain the case due to the continued growth in coal use in China and India. The EU and North America amounted to around 40% of the market share in 2013, although the replacement market for used parts and consumables may become more important than new sales. A Hexa Research study lists similar major company players to those mentioned above with the addition of China Boqi, Chiyoda Corporation and Longjing Environment (WDRB, 2016).

It is not easy to obtain a value for the global market for FGD, as most data searches lead to expensive marketing reports. However, it is clear that estimates vary and fluctuate annually. Back in 2013, a World Coal (WC, 2013) article suggested that the global FGD market would indeed fluctuate from year to year until 2020 and beyond, increasing from US$2.8 billion in 2012 to a peak of US$4.3 billion by 2016 and then dropping off to US$3.7 billion by 2020. Unsurprisingly, the majority of the initial market was in China, with 65.5% of global installations expected in the country between 2013 and 2020. However, a more recent press release for a commercial marketing venture suggests that the global FGD system market, including the market for industrial as well as power sources, could reach US$19.96 billion by 2021. The majority of these sales are expected to be in the power utility sector (M&M, 2016). However, with no detail on how these estimates are created, it is hard to determine how accurate they are likely to be. Potentially a new and significant sulphur control market will emerge soon in India. However, the timeline for this is somewhat unclear and there are various issues to resolve (*see* Section 4.6 for more details).

The market for sulphur control remains strong as more countries move towards better air quality. Growing energy demand, especially the growth in energy requirements for developing economies and emerging nations will ensure a large potential sulphur control market for the foreseeable future. However, it is suggested that the associated high operation and maintenance costs and waste stream issues could reduce the market for standard FGD systems in the future (WDRB, 2016). Emerging systems, which are smaller and/or modular, with alternative waste streams and lower water requirements systems could become more popular in the short to medium term.

5.2 USA

The USA has led on many standards for emissions, especially mercury. Although emissions trading approaches for SO_2 and NOx in the past led to some plants managing to delay installation of FGD and NOx control technologies, the new Mercury and Air Toxics standard (MATS) will generally ensure that all plants are installed with full flue gas control systems within the next few years. The new Clean Power Plan (CPP), currently being opposed by 26 states, is already causing some older plants to close and thus putting more pressure on the remaining plants to continue to provide power. Although low gas prices in the USA are often blamed for the continuing decline of coal use, many believe that it is the tightening legislation which is the cause. Coal capacity has dropped from 313 GW in 2008 to 279 GW in 2016 and is expected to drop another 24 GW by 2025. Around 13 GW of closure is reported to be due directly to the MATS rule (Moore, 2016; Hutson, 2016). It is unclear how this legislation may evolve or change following the inauguration of President Trump in 2017 as he has noted a desire to increase coal use in the country.

Whilst coal plants are closing and few, if any, new plants are being built, there is still a large coal utility sector in the USA and those plants remaining will have to run at higher capacity factors. These plants must comply with the EPA legislation and will therefore be required to install FGD, NOx control technologies and, in many cases, enhanced controls for mercury and fine particulates. There are over 400 units ≥300 MW still in operation and 63% of these are subcritical plants and 50% are over 40 years old. Plants in the USA, like those in the EU (*see* Section 4.3) have to balance the economics of retrofitting to comply with new emission limits with the remaining lifetime of the plant.

According to Hutson (2016), of the 279 GW of installed coal-fired capacity in the USA, 81% has some form of FGD technology installed (wet FGD 169 GW; dry FGD scrubber 42 GW; DSI 11 GW; and FBC with reagent injection 3 GW). Those without FGD are either smaller, older units or units firing low sulphur coals. For NOx control, around 48% of plants have either SCR or SNCR (SCR 104 GW; SNCR 31 GW) and 52% (144 GW) use combustion controls. However, some plants may have both combustion controls and SCR or SNCR. McIlvaine (2016) notes that 41 coal-fired units will undergo upgrading, including a US$700 million NOx control programme, over the next five years.

Figure 12 shows the change in USA capacity between December 2014 and April 2016 in response to new and impending legislation.

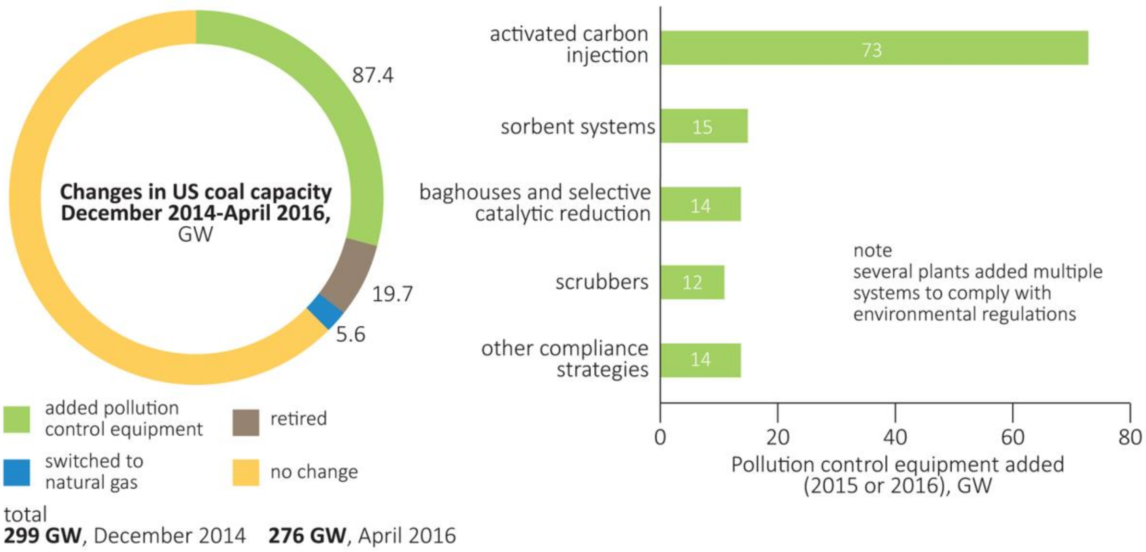

Figure 12 Changes in US coal capacity, December 2014 to April 2016 (EIA, 2016)

The pie chart on the left shows that just over 8% of the capacity in 2014 either retired or switched to firing natural gas. Another 62% did nothing – this was either because they were already in compliance or the plants have delayed installing retrofits (2.3 GW have one year extensions, many more had only until April 2016 to decide how to comply). This means that 30% of plants in the USA installed new pollution control systems over a relatively short 18-month period. Of the retrofits, the installation of ACI was by far the most common adjustment, as it was added to 73 GW of capacity. As noted in the diagram, several plants had to combine several systems to achieve the emission reductions required. It has been estimated that operators invested at least US$6.1 billion in this period (EIA, 2016).

Figure 13 shows the installation of control technologies across the USA fleet by 2015.

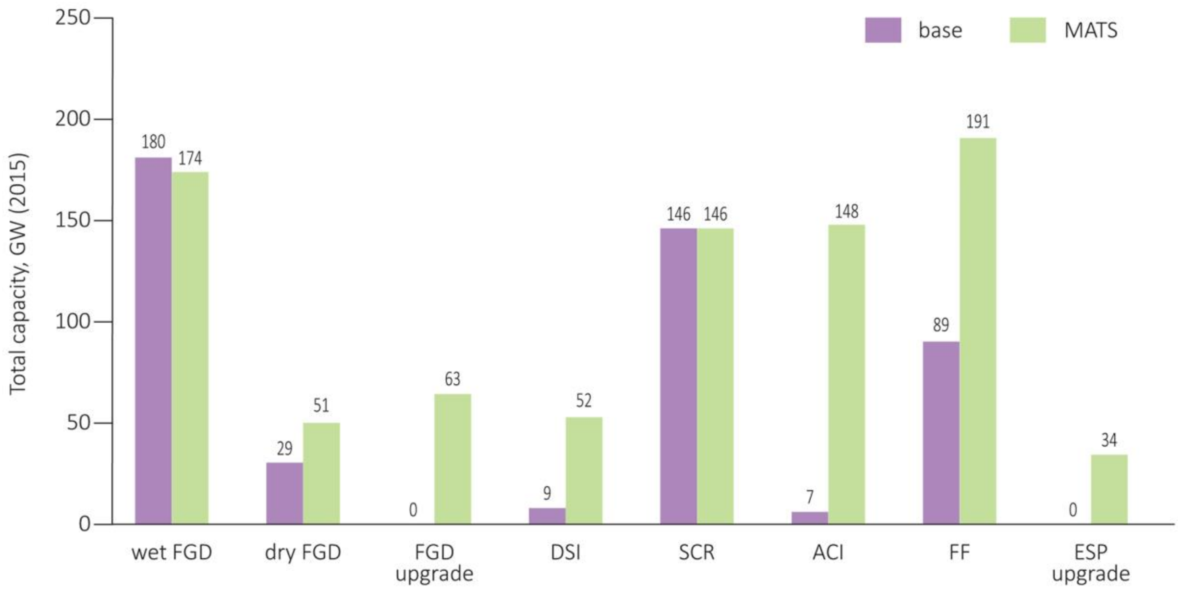

Figure 13 Installed capacity of controls in the USA (Hutson, 2016)

The bars in purple indicate the capacity of control systems considered the base case (no MATS) versus the bars in green which show the effect of MATS. It is clear that MATS appears to have caused a slight shift from wet to dry FGD systems, a significant growth in baghouse installation and associated sorbent injection, and some ESP upgrading activity.

As stated in previous IEA CCC reports by Wiatros-Motyka (2016) and Nalbandian-Sugden (2016), coal use for energy in the USA is expected to decline slowly, providing 21% of capacity in 2030 and 18% in 2040 (Wiatros-Motyka, 2016). The rest of the plants will therefore have to decide whether their remaining lifetime is enough to continue to bring in revenue, taking into account the cost of the retrofits which will be required to comply with current and impending legislation. However, more than half of the American coal fleet is over 40 years old and over 40% of the remaining units do not have state-of-the-art control equipment.

The new CPP, if promulgated and implemented, will limit CO_2 emissions from existing coal-fired plants. Although the compliance date has been moved back from 2020 to 2022, this rule is likely to affect decisions on retrofits to existing units before then (Martin and Jones, 2016). Managers of many older plants will have to decide whether further investment for compliance with existing rules such as MATS, will be worthwhile with further controls and limitations arriving with the CPP within the next 5–10 years.

5.3 Europe

According to the review by Wiatros-Motyka (2016), around 25% of the electricity produced in Europe is from coal, although the distribution varies from country to country. The majority of plants are over 25-years old. Around 91% of plants have ESP systems and just under 5% have either baghouses or baghouses in conjunction with cold side ESP systems. Only one plant is reported to have an advanced multi-pollutant control technology in place (SNOX), although there are reports of trials of newer systems at some plants (such as the Gore system in Poland, *see* Chapter 3). Around 88% of the plants have FGD in place and 86% of these plants use limestone-based FGD. Low sulphur fuel is used in around 8% of the fleet. Although data on NOx control systems is somewhat lacking, it would appear that the majority of EU plants have low NOx burners and/or overfire air systems. SCR is in place on around 31% of plants and only 4% use flue gas recirculation as a method for controlling NOx emissions.

New build coal in the EU is very slow with seven plants, all ultrasupercritical, in various states of construction (5 in Poland, 1 in Germany and 1 in the Czech Republic). Further plants are reported to be planned in Poland (5), Greece (1) and Germany (1). The EU's push towards renewables and the continuing tightening of emission limits for coal-fired plants is likely to lead to the reduction in further new build and the closure of a significant proportion of the existing fleet over the coming decades. For example, the UK and Germany plan to phase out coal use completely by 2025 and 2050 respectively. However, Poland has announced continued support for coal, and plans to invest up to €12.5 billion in coal-fired plants in the future (Wiatros-Motyka, 2016). Over 50% of Polish coal-fired plants are over 25-years old and 25% are over 30. Newer lignite plants are being retrofitted to meet new EU standards. However, as discussed by

Nalbandian-Sugden (2016), Poland is focusing on energy security which may push compliance with EU limits and associated retrofitting of control technologies further down the agenda.

The EU is currently supportive of renewables However, as discussed in the previous IEA CCC report on intermittency (Sloss, 2016), the move to renewables is proving challenging in terms of security of supply and balancing of the grid. Some member states such as Germany and the UK are already facing cost and availability issues and this is likely to happen in increasing numbers of countries in the coming years. Until the intermittency of renewables is solved, many existing, older coal-fired units will be required to work beyond their planned lifetimes and for reduced periods (only during peaking periods and periods when renewables are unavailable) which means that they are running as cheaply as possible as a necessity. Many of these plants, due to age and income, will not invest in significant upgrades and retrofits since they ultimately face closure.

Emission limits for particulates, SO_2 and NOx have existed in the EU for decades and have been tightened over time. The current emission limits sit at between 200 and 400 mg/m^3 for SO_2, 200 and 300 mg/m^3 for NOx, and 20–30 mg/m^3 for particulates, depending on plant size and some derogations remain for older plants running a limited number of hours before closure. Proposed changes to the LCPD (Large Combustion Plant Directive), BREF (BAT reference guidelines) could bring these limits down even further, to as low as 80 mg/m^3 for SO_2 and 50 mg/m^3 for NOx at newer, larger plants (Zhang, 2016).

Markets within the EU are varied. Most countries have until 2021 to install SO_2 and NOx controls and most plants have either done so, have plans on how to achieve it, or plan to close. However, Poland, with a more challenging economic situation, may derogate further for existing plants while new, cleaner, plants are built. So it is unclear whether in such countries older plants may delay retrofitting indefinitely until closure whilst newer plants incorporate control systems as part of their design. Both situations limit the retrofit market potential.

The major new consideration is the addition of mercury emission limits under the new BREF of the IED. Although not yet promulgated, it would seem that an emission limit range of 1–9 μg/m^3 will be set. The exact limit for each plant will depend on size, age, fuel and, ultimately, will be at the discretion of the local or national permitting authority. This means that some plants, especially those in countries which traditionally set tighter emission limits (such as Germany), may have to install mercury specific control systems. Although mercury control in existing particulate, SO_2 and NOx control systems is technically achievable, the extent to which it is done depends on factors such as the coal type and plant configuration (*see* Section 2.4). For many plants in the EU, this new legislation may introduce the requirement to install mercury specific controls and flue gas polishing techniques such as those seen in the USA. However, because many of these EU plants already have FGD and SCR systems in place, it is likely that those mercury controls which take advantage of these systems will dominate – such as oxidants. As mentioned earlier, the majority of coal plants in the EU are installed with ESP systems and many of these will not be suitable for sorbent addition in their current form. This could mean some upgrading of particulate control systems.

The new large combustion plant BREF is still under negotiation and so the proposed publication date of early 2017 may be pushed back further meaning that compliance will not be necessary until mid-2021 or beyond.

For countries outside Europe, breaking into the EU market can be a challenge. As mentioned in Section 3.4, the standards for equipment and monitoring differ – the EU uses CEN (Comité Européen de Normalisation) standards whereas the USA has its own standards. EU equipment based certification is design-based, and individual technologies have their own certification for use in certain applications. In the USA, any piece of equipment can be used as long as it meets design specifications. This means that, in some situations, especially for monitoring equipment, new USA equipment must be certified for use within the EU, a process which can cost hundreds of thousands of dollars (ITA, 2016).

The **UK, Germany and France** are either already in compliance with EU emission regulations or are planning to become so in the foreseeable future meaning that the market for retrofitting for particulates, SO_2 and NOx is largely for upgrading and maintenance. Early indications are that the German EPA propose to set an emission limit of 5 µg/m^3 initially for mercury, to be achieved within four years of the BREF, and then this would be further reduced to <1 µg/m^3 within 2–4 years, although this is still to be debated and confirmed. It has also been reported (in German) that lignite plants in the country cannot comply with the proposed emission limits using currently available control technologies. A number of German hard coal plants have allegedly been seeking advice on the potential use of oxidants for mercury control (Petzoldt, 2016). **Spain** has also installed FGD on most of its larger units and combustion controls for NOx (Mills, 2010).

As mentioned earlier, there will be an emerging market for mercury control in some regions in the EU when the new IED emission limits are finalised, particularly for flue gas polishing techniques. However, until the IED is agreed and adopted into national legislation in member states, there is still some uncertainty over just how stringent the emission limits will be on a plant-by-plant basis.

The rest of this section concentrates on EU countries which have potentially more challenging situations with respect to compliance with EC directives and may offer a continuing market for flue gas control systems.

According to the ITA (2016) **Poland** has lagged behind other countries in its adherence to EU standards and regulations with many delays and derogations. This, in turn, leads to delays in the purchase and application of control technologies. Many Polish plants will have to install FGD, SCR or SNCR, ACI and advanced particulate control systems to meet current and impending EU standards. However, Mills (2010) suggests that a significant amount of time and money has already been invested in upgrading and modernising the Polish coal fleet and modern emission control systems have been installed at 'many sites'. Compliance with the tightening requirements of the new IED BREF could cost the Polish power sector up to €5 billion (Zhang, 2016). Whilst some plants are delaying compliance, others are more forward thinking. For example, Polish utility, SBB, is fitting a state-of-the-art multi-pollutant control system to its Patnow II plant. The GORE system, as discussed in Chapter 3, is a modular fixed adsorbent system which can be used to capture both SO_2 and mercury and is one of the first systems of its type to be trialled at full scale at a coal plant in Europe (Zmuda, 2016).

Dulcea and Ionel (2015) note that existing coal plants in **Romania** (running coal or fossil fuel in general) which wish to remain competitive in the power market (without penalties due to emissions of pollutants) will have to comply with the NECD and similar protocols by 2020. Whilst these, and other newer EU members may have delays and derogations on compliance with EU emission limits, eventually they will have to retrofit the required technologies. Romania identified a significant need for investment in FGD at several lignite plants including Craiova, Doicesti, Isalnita, Poroseni, Rovinari and Turceni. Work on the latter was due for completion by 2014. NOx emissions are also of concern as the Turceni plant was identified as one of the top twenty NOx producing point sources in the EU. Low NOx burners are being installed at a number of plants and more are planned (Mills, 2010).

Bulgaria is being aided to comply with EU standards by projects such as ENEL's installation of FGD and low NOx burners at the Maritza III plant. €60 million is being invested at the 630 MW Bobov Dol plant. Interestingly a combined SO_2/NOx electron beam pilot project has been carried out at the 120 MW Svishtov plant converting 85% of the SO_2 and 40% of the NOx in the flue gas into dry ammonium compounds suitable for use as fertilisers. The **Czech Republic's** biggest power generator, CEZ, has been modernising the fleet and a total of 28 FGD systems have been installed, although some plants have still to undergo retrofitting (Mills, 2010).

Several coal fired plants in **Greece** have been retrofitted with wet FGD scrubbers and there are plans for further FGD installations at several other plants (Mills, 2010). **Hungary** also installed FGD systems at several power plants to allow early compliance with EU emission standards when it became a member of the EU (Mills, 2010).

Turkey is in Europe but not yet a member of the EU and, as such, is not required to meet EU standards, although it does have its own, somewhat less stringent, emission limits. The country has more than thirty lignite-fired plants >300 MW 'many' of which already have FGD in place. NOx control is largely in the form of combustion controls. Retrofitting such plants to meet EU requirements will require significant investment. According to Mills (2014) some larger plants now have FGD but several older plants and smaller units do not. Most are expected to be suitably re-equipped and rehabilitated as they are sold into the private sector and the lack of such pollution control equipment is usually factored into the purchase price. The cumulated pollution abatement cost for the Turkish electricity sector is estimated to be over €18 billion per year for the period between 2010 and 2025. The EU often funds or subsidises environmental projects and development in Turkey, and priority is given to bidders from the EU over those from the USA (ITA, 2016). However, a recent meeting of the Turkish President Erdogan with American executives revealed a new investment incentives scheme to increase the US$20 billion trade volume between the USA and Turkey. The project-based support instruments include corporate tax exemptions of up to 100%, customs duty exemptions, compensation of up to 50% on energy consumption expenses, and the abolition of interest on loans (ITT, 2016).

5.4 China

By the end of 2014, China had 1360 GW of power of which 66.7% was fossil fuel based and coal provided 90% of the country's total energy resources (Shumin, 2015). Between 150 and 200 GW more coal plants are reported to be under construction, all of which will be super or ultrasupercritical plants (Wiatros-Motyka, 2016). However, China appears to be reducing its coal growth rate. Johnson (2016) notes that construction has been halted on 30 plants and plans for 114 GW of new thermal coal plants have been shelved or postponed since the beginning of 2016. This will reduce the market for associated pollution control systems. An over-capacity of coal power means that the Chinese Government is considering exporting power to India, South Korea, Japan and Southeast Asia. This would require investment in long distance voltage lines but would reduce the need for new coal plants in these recipient nations (McIlvaine, 2016).

Emission legislation in China has tightened at an incredible rate; the limits are now among the strictest in the world (Zhu, 2016). Of the current plants 'all' have particulate and sulphur control and 95% have NOx control (the remaining plants are CFBC (circulating fluidised bed combustion systems) (Wiatros-Motyka, 2016). The remaining market for particulate, SO_2 and NOx control in China will therefore be upgrading and replacement of ageing control systems on existing plants and installation of control technologies on new coal plants. As mentioned in Section 2.1, in recent years ESP systems have been replaced with fabric filters or pulse-jet bag filters; ESP in the fleet has dropped from 95% in 2010 to 69% in 2015 and EP bag filters have increased from 5% to 31% during the same period. Over and above this, China is committed to upgrading particulate control by developing more advanced systems such as low temperature and WESP. Desulphurisation systems are installed on 92.8% of the existing fleet and the remaining plants are CFBC systems with in-built sulphur reduction. At least 65% of the desulphurisation systems in place are FGD (wet, dry and limestone based) technologies (Wiatros-Motyka, 2016). The costs of compliance with Chinese emission standards are high – US$41 million (2012) to upgrade pollution control equipment at older plants, with NOx control estimated at US$9.6 million per year (Nalbandian-Sugden, 2016).

The new Air Pollution Prevention and Control Law of 1 January 2016 requires much more action at the regional level to ensure compliance with emission and air quality standards. China has also ratified the Minamata Convention which will require efforts to reduce emissions of mercury. If these, and the other existing and imminent emission control requirements, are implemented, then the market for control technologies in China should be significant, including requirements for the following (ITA, 2016):

- continuous emission monitoring systems;
- dry sorbent injection systems;
- FGD systems;
- ACI systems;

- ESP systems (wet and dry);
- SCR; and
- additional engineering systems such as inspection, adjustment, maintenance and repair services.

These systems would be required for both new plants and for replacement and upgrading systems in older plants. Although all large-scale plants in China have FGD and NOx control systems in place, some of these are old or not functioning sufficiently to meet the newer standards. And new plants are still being built. So there is still a market for control technologies in the country.

The Shenhua Guoha Power Company claims to be leading the field in terms of clean coal energy, aiming for near-zero emission HELE technologies. Target emission levels for the company's fleet are shown in Table 9.

Table 9 Target emission levels for coal-fired plants in China (Shumin, 2015)

	Particulates, mg/m^3	SO_2, mg/m^3	NOx, mg/m^3
Limits for new coal plants in China*	20	50	100
Limits for gas turbines in China†	5	35	50
Shenhua Guoha target for coal units*	5	35	50

* O_2 = 6%; † O_2 = 15%

The limits in Table 9 indicate the Shenhua company's commitment to building coal plants that are as clean to run as gas-fired plants (Shumin, 2015). According to Shumin (2015) in order to comply with these stringent limits, the company has been investing in control technologies 'from China and abroad'. The coal used in the Shenhua fleet is relatively clean – 0.4–0.8% sulphur, 7–16% ash and 0.08 mg/kg mercury (below half the average mercury content of coals used in China).

In order to move towards near-zero emissions, Shenhua has summarised the most appropriate technical option for new coal-fired plants in its fleet, as shown in Figure 14. The first link is a low temperature economiser (LTE). The lower temperature of these systems reduces the flue gas velocity and the resistivity of the particulate matter, increasing the efficiency of capture of particulates in the ESP system. WESP systems are reported to have a particulate matter removal efficiency of 70–90% – this is more than the >99% capture achieved in the ESP or fabric filter upstream. Next, the plant has a wet FGD system (98-99% efficient for SO_2). For NOx removal the plant uses both an in-furnace low NOx combustion system and a flue gas denitrification system (unspecified, >85% NOx control) (Shumin, 2015). As is common in China, Shenhua has developed and patented its own technology to enhance the performance of FGD towers which can improve SO_2 capture to more than 98%, reducing emissions from their plants to below 35 mg/m^3 (Shumin, 2015).

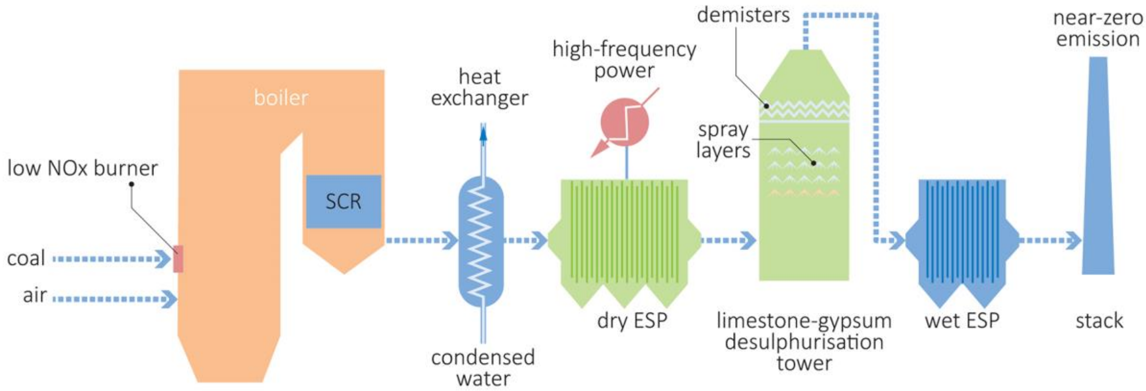

Figure 14 Technical option to achieve near-zero emissions from coal-fired units (Shumin, 2015)

There are currently nine coal-fired plants run by the Shenhua group in China which are defined as near-zero emission plants.

Wiatros-Motyka (2016) notes that one of the main drivers for emission reduction in China is the subsidies provided as feed-in tariffs for those power plants which are regarded as ultra-low emitters. An article in Reuters (2015) also notes that China is now offering bonuses to coal-fired power plants to meet new emission limits. The funding is supposed to help promote clean power whilst some debt-laden generators struggle to maintain and upgrade their plants during the recent slowing of economic growth. New plants (after 1 January 2016) which meet the new environmental standards will get 0.005 yuan/kWh on top of the basic grid tariff. Those already in operation would receive an additional 0.01 yuan/kWh, equivalent to about 42 million yuan (US$6.5 million) if all thermal power output last year were produced at plants meeting the coal efficiency standards. The higher tariffs will take effect in January 2017 and last until the end of 2017, when the government will reassess the rate.

Liu and others (2016) argue that this incentive is insufficient to cover the FGD costs of most of the seven sample plants they considered. Instead they suggested a more supportive financial environment for the FGD industry using fiscal supports, diverse access to finance, and innovative financial and business models.

Conversely, Shumin (2015) also considered the extra income through adjusted tariffs for plants with control technologies and reported that the tariffs would indeed be beneficial in encouraging cleaner plants. The rates considered were:

- plants with particulate removal systems have a feed in tariff of 0.2 RMB/kWh (0.032 $cents/kWh);
- plants with desulphurisation systems have a feed in tariff of 1.0 RMB/kWh (0.24 $cents/kWh);
- plants with denitrification systems have a feed in tariff of 1.0 RMB/kWh (0.16 $cents /kWh); and
- plants with all three systems in place have a feed in tariff of 2.7 RMB/kWh (0.43 $cents /kWh).

According to Shumin (2015), the cost of retrofitting the plant to meet near-zero emissions would be RMB 0.5–2.0/kWh (0.08–0.32 $cents/kWh) and so it is possible that investment would pay off in terms of income covering costs. Over and above this, Shumin stresses that coal-fired plants are still significantly cheaper than natural gas combined-cycle units in China (less than half in terms of cost per kWh).

Shumin's article did not mention whether the control technologies used at these plants were made in China or imported, but the balance of costs would imply that the government's adjusted feed in tariff plan could make importing new technologies more affordable.

Back in 2008, Jessup (2008) reported that the Chinese Academy of Sciences had recognised the potential for China to develop clean coal technologies for both the foreign and local market. Between 1979 and 2008 there were 41 Chinese patents for clean coal technologies and 18 locally-developed technologies were in use, ranging from power generation systems to pollution control equipment. However, it was also noted that international inventors of clean coal technologies sell their products in China with the expectation that they will have the exclusive rights to distribute the technology in all countries. IPO (2016) gives advice on best practice for technology transfer to China, outlining the requirements for IP considerations and summarising taxation implications. Li and others (2015) note that the clean coal policies and energy situation in China have a significant effect on the innovation and patent rate in the country. The coal price shock of 2015 was reported to be expected to have a significant effect on increasing the rate of patents in clean coal technology systems. However, it was noted that such effects are rarely long lasting and that the government investment in pollution control systems is the major driver behind developments.

The ITA lists the major market barriers to the sales of environmental technologies into China (ITA, 2016):

- Complex intellectual property environment – intellectual property rights infringement is common.
- Demonstration projects are often required to show equivalence or superiority to reference technologies and this may be at the supplier's expense. They may have to be repeated in different provinces with alternative environmental rules.
- Preferential procurement – State Owned Enterprises may crowd out competitor technologies to create a state-sponsored monopoly. The Chinese Government has included environmental technologies as one of the strategic industries intended to generate growth in domestic consumption. Over and above this, government tenders often express explicit preference for domestic bidders over foreign tenders.
- Many international certification systems are not recognised in China whilst national certification is available only for locally produced equipment.
- Political disincentives – environmental rules are enforced at the local/provincial level and may come second to issues such as economic growth. This may be remedied by the new Environmental Protection Law (EPL) which aims to enforce environmental legislation and penalise non-compliance.

And so the future market for emissions control technologies in China is complex. The majority of the existing fleet are relatively efficient and already have emissions control technologies in place. There may be some continuing market for upgrading remaining ESP systems to fabric filters or WESP, especially newer multi-pollutant systems which may be able to reduce emissions of emerging pollutants of concern such as fine particulates and heavy metal species. However, the phasing out of older and smaller plants will mean that the retrofit market will only be a fraction of the older plants currently still operating. New build plants in China have to be large (>1000 MW) and have particulate, SO_2 and NOx control systems in place from the first day of operation. Forward thinking utilities in China, and those who wish to take advantage of the enhanced feed-in tariffs for cleaner plants, are likely to invest in advanced pollutant control systems, such as wet ESP and EFIC. And many of these systems will be developed and marketed at home in China. China is then quite likely to have the capacity and the materials ready to lead in international sales of these types of equipment. According to Wiatros-Motyka (2016), China now competes with Japan to export advanced control technologies and continues to invest in R&D in this area.

5.5 Japan

The Japanese coal fleet (just under 35 GW) consists of 48% supercritical and 47% ultrasupercritical units, with only 5% subcritical units remaining. Although the emission data are seldom published, Japanese power companies pride themselves on having the cleanest plants possible and so all are assumed to have FGD in place (over 90% had wet FGD by 2000) and at least 75% of plants have both low NOx burners and SCR systems in place, the rest having either one or the other (Wiatros-Motyka, 2016). Several plants have state-of-the-art systems such as WESP and low temperature ESP in place and the ReACT system for advanced SO_2, NOx and mercury control is installed in at least one plant. Current focus on emission control in Japan appears to be on CCS.

Japan exports HELE technologies and emission control systems and invests heavily in increasing the performance of coal plants overseas, investing over US$19 billion between 2013 and 2014 in funding for clean fossil fuels. This includes work in the Ukraine to modernise the ageing coal fleet, and funding for clean coal technologies in Thailand, Indonesia and Chile (Wiatros-Motyka, 2016). This means Japan is not a potential target for sales of emission control technologies but instead is a leader in the installation of these systems overseas.

5.6 India

Considering that until this year, India had little or no emission limits for coal-fired plants, the recent move to adopt standards at the same level as those seen in the EU and China is a significant challenge. A previous report from the IEA CCC (Sloss, 2015b) focused on potential options for reducing emissions from the Indian coal sector in the face of the inevitable increase in coal use in the country. The following sections look at the standards and how the required emission controls may be achieved in practice.

India has around 176 GW of coal plants, providing 61% of the total capacity (other major contributors are hydro 15%, renewables 13% and gas 8%) (Kassi, 2016). India's coals are relatively low in sulphur (around 0.5%). However, the sheer volume of coal combustion in the country means that emissions are still of concern and, of the 80,000 deaths in India estimated to be due to coal-fired power plants in 2011, 60% of these are associated with the SO_2 emissions (Cropper and others, 2016). A high ash content in coal is a significant issue in India, not least since many of the technologies required for emissions control, such as FGD and SCR systems, are known to have issues with high ash coals but have not been extensively tested to determine the extent of the problem (Sinha, 2016).

There is significant concern in India over the sudden appearance of these new norms and the short period allowed for compliance. Kassi (2016) suggests that the legislation will lead to periods of closure for many plants to allow for retrofitting and that this will cause issues with the grid and the power supply. Retrofitting may need to be carried out in a staggered manner to maintain power output. Units working at a low profit margin or which run seasonally or intermittently may be unable to see any return on investment for their remaining lifespan and would have to counteract this with a steep rise in the power tariff.

Table 10 shows the new emission standards or 'norms' which have been set in India. The emission limits are similar to those currently set for most plants in China and, as such are relatively challenging. The legislation is split according to plant age and size – before and after 2003, <250 MW, 250–500 MW and >500 MW. With respect to plants built before the end of 2013, there are currently none over 500 MW and only 27 units (totalling 13,500 MW) in the range of 250–500 MW. The majority of plants (313 units totalling 47,628 MW) are smaller than 250 MW (Kassi, 2016). Since these plants are smaller and older, the investment in upgrading and retrofitting may be less of a priority than for newer units.

Table 10 New emission norms in India (EEC, 2016)

Emission parameter	TPP* (units) installed before 31/12/2003	TPP* (units) installed after 31/12/2003	TPP* (units) to be installed from 01/01/2017
Particulate matter	100 mg/mg^3	50 mg/mg^3	30 mg/mg^3
Sulphur dioxide (SO_2)	600 mg/mg^3 for units <500 MW 200 mg/mg^3 for units 500 MW and above capacity	600 mg/mg^3 for units <500 MW 200 mg/mg^3 for units 500 MW and above capacity	100 mg/mg^3
Nitrogen oxide (NOx)	600 mg/mg^3	300 mg/mg^3	100 mg/mg^3
Specific water consumption limit	Cooling tower to be installed in place of once through cooling and water consumption up to 3.5 m^3/MWh maximum. Water consumption of up to 3.5 m^3/MWh for all existing cooling tower-based plants		Maximum water consumption of 2.5 m^3/MWh and zero wastewater discharge
Mercury	1. TPP (units) installed before 31/12/2003 (500 MW and above capacity) 2. TPP (units) installed after 01/01/2003 up to 31/12/2016 3. TPP (units) installed from 01/01/2017		0.03 mg/mg^3

* TPP = thermal power plants

These 'norms' are mandated to be complied within two years by all existing units of TPP and from 01/01/17 by all new units of TPP

Most units currently in operation are designed to meet an emission limit of 50 mg/m^3 for PM (referred to as SPM – suspended particulate matter in India) and so the new standard should not require anything more than confirmation of compliance. The tighter limit for new units will require more state-of-the-art particulate control systems (EEC, 2016).

According to the EEC study, upgrading or replacement of existing ESP and baghouse systems and perhaps temperature control and flue gas conditioning at some plants should be sufficient to achieve the particulate emissions limit. Singh (2016) of the Central Electricity Authority in India, notes that many plants with ESP systems will require the retrofitting of additional ESP fields or, in some cases, complete replacement of existing systems.

Low sulphur content fuel (<0.2% sulphur) could be used to achieve compliance for the sulphur limits at these older plants. For the larger units, the use of FGD will depend on the availability of space for retrofitting. For newer units (2003-16 and beyond) 'most' units >500 MW have space available for FGD (wet or dry) retrofits to comply with the tighter sulphur emission limits. Space constraints at smaller units may make FGD retrofits unfeasible and this could be an issue with respect to compliance. According to Kassi (2016) about 80,000 MW capacity of <500 MW units will not have sufficient space for FGD retrofitting. Singh (2016) gives a higher estimate of 95,000 MW capacity which would be affected by space issues. On these plants, smaller, modular control systems may be more appropriate.

Sinha (2016) looks at the decision making process for sulphur control in India, noting that dry FGD systems can often retain and use the existing stack structure whereas wet FGD systems would require modification of the stack 'in all cases'. Those plants which do choose to install FGD will be involved in installation periods of 2–3 years involving plant shutdowns of 4–6 months (EEC, 2016). Sinha (2016) gives erection times of 24 months for dry FGD systems and 30 for wet FGD systems. As mentioned earlier, since India is already short of power, shut-downs are avoided as much as possible. The reduction of 1–1.5% plant power output due to power consumption in the FGD systems could also be seen as an issue. If FGD were installed on 200,000 MW of coal-fired capacity, then this would require 24 Mt/y limestone and would produce 34 Mt/y gypsum per plant. Resources of limestone in India and transport options have still to be addressed. It has been suggested that plants with FGD in place in India are already reporting issues with gypsum disposal (EEC, 2016). However, Sinha (2016) reports that there are over 700 limestone mines in India with production totalling 278.7 Mt/y. The limestone has 80-85% purity and is mainly sold to the large cement market in India. Significant increases in mining rates may be required to cope with the demands of FGD installations. There is therefore a potential market for desulphurisation technologies which do not require limestone.

The total cost of compliance for Indian coal-fired plants with the new norms has been put at US$37 billion and, with the date for implementation of the plan (December 2017) looming soon in legislative terms, there is much speculation about whether the new norms can and will be applied in practice (McIlvaine, 2016).

Sinha (2016) lists the challenges faced for desulphurisation in India:

- all SOx control technology options are new to the Indian utility sector, despite how mature they are in other regions;
- wet FGD system is the most popular option for SO_2 control worldwide but requires significant amounts of water which would be a problem in many inland locations;
- limestone supply and gypsum disposal need to be addressed; and
- FGD retrofit may simply not be technically possible (due to space and design constraints as well as economics) at older stations.

Cropper and others (2016) have estimated the comparative costs of FGD in India, based on data from the Dahanu (seawater FGD) and Bongaigaon (wet FGD) plants already in operation. However, since both those plants were new build, costs were increased by 30% to reflect the higher cost of retrofit systems. The comparative costs were as shown in Table 11.

Table 11 Cost calculations for FGD systems in India (Cropper and other, 2016)

	Wet FGD system	Seawater FGD system
Capital cost, US$/MW	90,910	70,300
Fixed operating costs, cents/MWh	37.9	28.8
Variable operating costs, cents/MWh	0	0
Auxiliary consumption, %	1.5	1.25
FGD efficiency, %	90	90

Based on the numbers in Table 11, Cropper and others (2016) estimate that the capital costs for FGD installation at each of 72 plants in India would amount to US$110 million, and the operating costs would be US$2.6 million (per plant). It is possible to identify the plants with the greatest emissions and to prioritise these based on the potential to save the greatest number of lives and this could be the most cost-effective move for the country.

Low NOx burners may be adequate for NOx control at some older plants but this would need to be confirmed in practice. SNCR is an option but comes with potential issues in terms of ammonia availability and control and is generally only applied to smaller units (<200 MW). SCR may be a useful option at larger units but is regarded as costly. As with FGD systems, space and plant configuration may be an issue at some older plants. Some SCR systems require changes in ductwork and ID fans which could cause problems. Ammonia consumption could also be an issue with 2500 t/y required for a 500 MW unit, adding to concerns about availability, transportation, handling and storage (Kassi, 2016).

To date there is no experience with SCR systems at plants firing high ash Indian coals (EEC, 2016; Kassi, 2016). As mentioned in Section 2.3, high ash coals can cause issues with SCR systems and, since Indian coals are high in ash, this problem will need to be addressed for Indian plants. Sinha (2016) has suggested possible plant configurations to cope with high ash Indian coals, as shown in Figure 15.

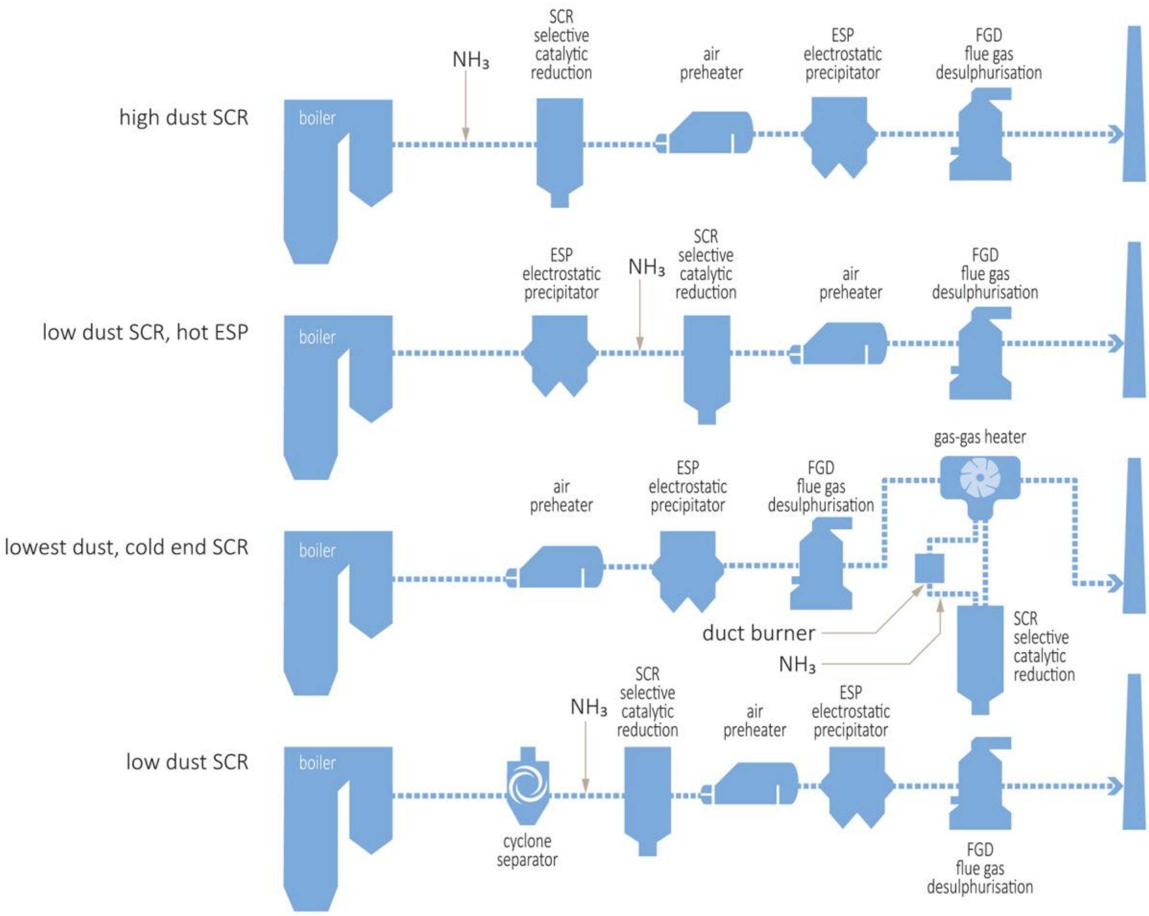

Figure 15 Possible SCR configuration to deal with high ash (Sinha, 2016)

As shown in the figure, there are several possible options to reduce the dust loading on an SCR system firing high-ash Indian coals. The first option is to invest in a high dust SCR system. However, since there is no experience of the efficacy of such systems with the very high ash contents of Indian coals, it is unclear how successful these systems would be. The alternative approaches involve either upgrading or replacing the existing particulate control systems to cope with the higher ash and remove it before the flue gas reaches the SCR system. Whilst this may make sense in theory, there are likely to be significant issues in practice, not least potential challenges with existing plant layout and space availability. For example, as mentioned previously, SCR systems often require adjustment in ductwork and ID fan configuration which could be an issue at some units (Kassi, 2016). Add in new particulate control systems and the challenge increases significantly (Sinha, 2016). SCR systems in India would have to cope with particulate concentrations up to three times higher than seen in most other countries. SCR catalysts are regarded as expensive, requiring replacement every 1–2 years and there are currently no SCR suppliers in India.

JGC (Japan) have studied the ash issue for SCR systems in high ash situations such as in Indian plants. Ideally the SCR system is located in a low dust position, downstream of both the particulate control system and the FGD (if present). Changes to the materials used to construct the catalyst can result in a structure which is reinforced to prevent erosion by ash. Modification of the pore size can also help to avoid clogging

(Nakamura, 2016). And so it is already the case that forward thinking companies are analysing the potential for the emerging control market in India and are adjusting their products accordingly.

EEC (2016) and Sinha (2016) state that "no mature technology is available for control of mercury" which is incorrect. As discussed in Section 2.4, many commercial systems are available and even standard particulate, SO_2 and NOx systems can achieve up to or over 80% mercury control in some instances. Considering that mercury specific control options such as oxidants and activated carbon can bring additional cost and plant issues, mercury control through co-benefit effects at Indian plants makes sense. The emission limit of 30 μg/m^3 should be easily achievable through well managed co-benefit effects at plants with FGD systems in place. The UNEP Coal Partnership and the IEA CCC have worked together to produce several reports relating to the evaluation on mercury emissions from coal combustion in India and potential options for control. These are available as free downloads from: http://web.unep.org/chemicalsandwaste/global-mercury-partnership/mercury-control-coal-combustion/reports-and-publications

It is interesting to note that the Indian standards in Table 10 include a limit for water consumption, recognising the issue of water availability in the country. Plant designs will have to change to switch from once through cooling water systems (OTCW) to closed cycle systems and this may not be possible with the current layout and space availability at some plants. According to the EEC (Excellence Enhancement Centre for Indian Power Sector, 2016) the typical land requirement for converting 2 x 500 MW units to closed cycle with induced draught cooling towers is around 65 acres (26.3 ha). This increases to 80 acres (32.4 ha) if natural draught cooling towers are used. Seawater cooling systems have to deal with higher concentrations of dissolved solids and have greater rates of water consumption – 8 m^3/MWh, exceeding the new water limits. This means that coastal plants cannot comply with the new norms and, unless the norms are changed, these plants will need to close (EEC, 2016). Low water and dry cooling systems are discussed in a CCC report by Carpenter (2012).

India appears to be emerging as a potentially huge market for emissions control technologies. The Union Power Ministry has mandated clean coal technologies for all new coal-fired plants. However, Kassi (2016) suggests that the biggest constraint on flue gas control installation in India is actually the availability of vendors. At the moment, flue gas control systems have to be imported as there is limited indigenous manufacture or availability. BHEL (Bharat Heavy Electrical Limited) and possibly Thermax are currently the only Indian companies that can supply state-of-the-art coal-fired plants with the BHEL company supply capacity representing 73% of the total power generated in the country.

Sinha (2016) notes that, despite control technology options being commercially available and established in many developed regions, the applicability of these systems to Indian coals has yet to be determined and that, as a result, at least 5–7 years should be allowed for older plants to comply with the new Indian norms.

Thermax appears to have a large share of the market for the installation of ESP on units <300 MW in the country and Balcke Dürr supplies ESP for units >300 MW. Ducon Technologies India is supplying one of the first FGD systems for the 1015 MW Hyderabad Lanco plant and a subsidiary of Ducon has won the contract to install a similar wet FGD system on a 750 MW NTPC plant in Assam (Pai, 2016).

EEC (2016) noted that installation of flue gas controls on Indian plants at a rate of 20,000 MW/y on the total 266,000 MW capacity (185,272 MW existing plants and 80,800 MW under construction) would take over 10 years. Over and above this, there could be additional delay due to the required staggering of retrofits and shut-downs to ensure continuation of supply. Since it is likely that there will be an issue with compliance within the tight timeframe prescribed, it is possible that new plants would be delayed, affecting power availability and putting further pressure on existing units. Several Indian power companies have already raised concerns over the tight compliance requirements. Costs for upgrading will probably lead to an increase in power tariffs for consumers from 45–55 paise/kWh (paise is 1/100th of a rupee, making the price change under US$0.01). Older plants with limited lifetimes remaining may be unable to recover retrofit costs. Further, the significant demand for FGD and NOx control technologies in the international market could lead to availability issues and potentially lead to cost inflation (Kassi, 2016).

In order to ensure that the correct systems are installed in India, Kassi (2016) proposes the following:

- station specific studies on plant configurations and appropriate retrofit options for each;
- determination of space requirements for different systems;
- determination of plant modifications required;
- evaluation of limestone availability and delivery logistics and similar evaluations for gypsum usage or disposal;
- evaluation of additional water consumption and treatment/disposal issues; and
- definitive time and cost estimates for retrofitting.

A few case studies at Indian plants could go a long way to addressing concerns and would allow plants to move forward with devising plant specific strategies.

The ITA (2016) listed the main market barriers to the movement of international control technologies into the Indian market place:

- High tariffs –for environmental technologies and high import taxes reduce the competitiveness of more expensive international options.
- Fragmentation of the market – India is a large country with great regional variations making it hard for one vendor to represent the whole country. Resources must be deployed on a regional basis.
- Transparency and price sensitivity to tenders – transparency is an issue and tenders are often decided with a lowest bidder mentality, without full considerations of trade-offs between quality and cost.
- Corruption – reportedly rife at many levels.
- Compliance – poor enforcement of rules and laws. Prime Minister Modi's government has proposed 'the concept of utmost good faith', hinging on voluntary monitoring and disclosure of pollution

control by Indian businesses, which may not achieve the desired effect at the industrial level. Compliance may be more regulated for utilities.

- Limited experience of local partners – many of the sectors, issues and technologies are new to the Indian market which increases the management burden for international ventures.

The key technologies required in India will be (ITA, 2016):

- wet and dry scrubbers;
- baghouses;
- filters;
- FGD; and
- SCR and SNCR.

There is then the balance between what can be produced nationally and what must be imported. The Indian government has a 'Make in India' initiative to increase Indian manufacturing which includes the power generation sector within the target sectors for this initiative (ITA, 2016). However, building up the knowledge and skill set to provide the technologies required at the volume needed is unlikely to happen without significant international help and investment.

Oono (2016) of the Japan Bank for International Cooperation (JBIC) listed the key challenges identified in stakeholder interactions in India, including 'suspect' sanctity of Power Purchase Agreements (PPA) from a view point of external investors and non-standard risk allocation between parties as compared with international PPA. JBIC has therefore invested in joint venture companies between India and Japan which maintains the 'Make in India' government approach whilst allowing foreign investment and development.

Although there is a control market which is scheduled to emerge in India under new legislation in the next few years, the complex situation and the many challenges faced by the country result in a confusing contrast of potential sales versus likely sales. Whilst the control market is imminent, it is likely to evolve in an unpredictable manner for the first few years while the country balances what it hopes to achieve and what it can actually achieve, taking technological, hydrological, geographical, personnel and economic challenges into account.

5.7 Indonesia

Indonesia is a growing economy with US$1162 billion required to be spent on infrastructure before 2030. The Japanese have been financially supportive of growth in the country and have confirmed funding for a 2000 MW Batang Power coal-fired plant, following the initial delay of this project. Confidence in investment in the area fell after the 1997 Asian financial crisis. However, growth is necessary since the country is plagued by blackouts and electricity shortages. The country is expected to add to its electricity capacity of 47.3 GW in 2013 with a further 35 GW of power. Around 23% of this is already completed or under construction and a further 27% will commence soon. Even if the country falls short of this target, the growth was still expected to be significant (FT, 2016). However, the latest indication is that the country will only reach 20% of its development target of 97GW) by 2019. Some plants from the original fast-track programme are running at only 30–45% of planned output. The planned high-voltage line to connect three power plants in Sumatra with Java has also been abandoned (FT, 2017).

Indonesia has emission limits for particulates (100–150 mg/m^3, depending on plant age), SO_2 (750 mg/m^3) and NOx (750–850 mg/m^3, depending on plant age). In some cases, these emission limits can be met with compliance coals or combustion modifications and so retrofitting of flue gas cleaning systems is not required on all plants (Zhang, 2016). Most of the largest stations are equipped to modern standards with particulate control and FGD, and some are fitted with low NOx burners. A total of 8 GWe of capacity is fitted with some form of SO_2 control, either through scrubbing or boiler sorbent design. This accounts for 80% of the coal-fired capacity. More than 8 GWe of coal-fired capacity is also fitted with particulate filters, while 4 GWe have NOx control mainly from low NOx boiler design. However, this leaves a 'significant amount of capacity' which may require emissions control in the future. A further 12,000 MW of new coal-fired capacity implies a continuing pollution control market into the future (Baruya, 2010).

Indonesia has movement towards increased environmental control but has many of the economic and geographical challenges seen elsewhere in developing Asia. ITA (2016) list the major challenges in the country as:

- weak technical capacity to implement environmental controls, leading to delays in project development and weak administration of existing projects;
- poor asset management in public projects leading to infrastructure failure. Maintenance and upkeep tend to lapse and accountability is lacking;
- delays – from financing onwards. The Public Private Partnership model is flawed in that the risk is held entirely by the finance sector leasing to a hesitant market; and
- lack of regulatory implementation, transparency, and corruption in public tenders.

The market in Indonesia should be opening up for technologies such as continuous emissions monitoring systems (CEMS), dry sorbent injection (DSI), FGD, ACI SCR, SNCR and ESP (ITA, 2016).

5.8 South Africa

South Africa has adopted new emissions limits for particulates (50 mg/m^3 for new plants and 100 mg/m^3 for existing plants; referenced to 10% O_2), SO_2 (500 and 3500 mg/m^3 respectively) and NOx (750 and 1100 mg/m^3 respectively) which effectively require FGD and NOx control systems to be installed on newer units (Zhang, 2016). However, the energy situation in the country is challenging. Demand exceeds supply to the point that black outs and brown outs are not uncommon, although things appear to have improved within the last year. Removing a coal-fired plant from the grid to retrofit control technologies is still problematic. Add to that the cost issue and water availability restrictions and the combination makes it hard for the existing coal fleet to comply with the new legislation whilst still providing power. At the moment, the majority of South Africa's coal plant upgrade involves high frequency transformer upgrades.

Of the 15 coal-fired plants in operation in the country, six have fabric filters, seven have ESP and flue gas conditioning and two plants have a combination of both. A fabric filter retrofit is planned for Kriel and Grootvlei and FGD systems are planned for Kendal and Medupi. The new Kusile plant, expected online next year, will have fabric filters and wet FGD installed from the offset (Eskom, 2016). So, although FGD systems and NOx control are required on most if not all plants, only two plants are moving towards retrofitting FGD and the remaining plants will be upgraded when time and economics allow.

5.9 Other countries

Australia has less stringent emission standards than the EU and North America – there is nothing set at the national level on emissions of particulates, SO_2 and NOx and nothing of note at the state level. Australian coals are low in sulphur. The priorities for the country appear to be efficiency and CO_2, although the repeal of the carbon tax in 2014 and the continued delay of the National Plan for Clean Air (NPCA; Nalbandian-Sugden, 2016) would imply that, although there could be a future market for emissions control in Australia, it may be a number of years off.

South Korea has tightening air quality standards **which** should be creating a market for CEM, DSI, FGD, activated carbon injection and related technologies. However, South Korean companies have a tendency to be able to buy quality at low prices which is challenging for companies exporting to South Korea. The Korean standards are also different from international standards in some areas and this may mean additional testing requirements for imported technologies (ITA, 2016).

Thailand has emission limits for particulates, SO_2 and NOx which are relatively lax for existing units (180, 820 and 2002 mg/m^3 respectively). Mae Moh, the largest plant in the country, has a more lenient emission limit for NOx (1025 mg/m^3) but a tighter limit for SO_2 (915 mg/m^3). For newer plants over 50 MW the emission limits are 80 mg/m^3, 410 mg/m^3 and 515 mg/m^3 respectively, meaning that flue gas controls are largely required (Zhang, 2016).

Vietnam has a volatile energy sector which appears to be investing heavily in new coal capacity (Baruya, 2014). There are currently 26 coal plants in operation totalling 13.8 GW of capacity with a further 15 plants totalling an additional 14.6 GW of capacity under construction. Under the current development plan, the country will more than double its coal capacity to over 55 GW (52 units) by 2030. 'Most' plants have ESP systems in place along with wet FGD. Some plants are CFBC systems which use limestone in the bed system for sulphur control and cyclones for particulate control (UNEP, 2016).

Russia and neighbouring regions lag somewhat behind other regions with respect to emission control legislation. However, Russia has been involved in emission reduction studies such as those carried out in conjunction with the UNEP Coal Partnership and so such considerations may be moving up the national agenda.

5.10 Comments

The USA, many EU member states, and Japan for example have relatively mature pollution control marketplaces and the majority of plants are already fitted with the required control systems. A few upgrades and retrofits may still be planned, but a significant proportion of the future market will be repairs, operation and maintenance. New build in these regions is also restricted and so any new market is not likely to be significant and may be several years away.

Several countries have been identified as having continued growth in the coal sector, and requirements for control systems to meet new emission standards. Each has their own issues and challenges. Although significant retrofitting has taken place at many plants, Poland lags behind the rest of the EU somewhat in terms of compliance with emission limits; the major issue is economics as it could cost up to €5 billion to bring the remainder of the Polish fleet into compliance. Similar issues can be seen in Romania, Bulgaria, the Czech Republic and Greece, where the continued move to install control systems is a financial challenge. To become an EU member, Turkey will have to spend over €18 billion per year in the pollution abatement sector between 2010 and 2025. The country's President Erdogan has recently announced significant financial incentives to international developers wishing to move into the Turkish market.

Theoretically China is a huge market for pollution control systems and many international companies have managed to build a Chinese client base. However, China excels at mass-producing equipment quickly and cheaply and so is a challenging market to make profitable for an outside supplier. In fact, China has recently become a significant exporter of advanced control technologies and continues to invest in national research and development in this area. New subsidies to reward electricity production from cleaner plants could help improve the affordability of control technologies but imported systems will still have to compete with nationally produced equivalents. Perhaps the most important factor for international sales into China is the immense scale of the country – with so many existing and planned plants, the market for control technologies is large and will remain so for many years, meaning that there is space for international sales provided they can meet local requirements in terms of performance and cost.

Similarly, India is the largest emerging market for emissions control. However, although the potential market is huge, it is likely to develop in a sporadic and unpredictable manner. Most plants in India have only basic particulate control systems and so, in order to comply with the new emission limits, flue gas cleaning systems will be required on almost all of the existing and new fleet. This poses a huge challenge in terms of materials and skills availability, over and above the immense cost. Other than BHEL, India has little national expertise in plant engineering and currently has few, if any, national suppliers of FGD and SCR technologies. On top of this, India has a shortage of power and so the removal of plants from the grid for upgrading and retrofitting will be costly and will have to be staggered to ensure a consistency of electricity supply. Focusing on more national issues, India also has limited water availability, meaning that the market may be skewed towards systems with lower water requirements. India also has extremely challenging coals, sometimes over 40% ash – most commercially available pollution control systems have not been applied to plants firing these kinds of materials. This makes it harder to predict problems and to determine which system is best for each Indian plant. There is therefore a need for demonstration projects of various control options at Indian plants in order to determine which systems are best suited to the Indian challenges. India could potentially offer an excellent chance for newer, modular, multi-pollutant technologies to demonstrate their applicability, providing they prepare for the low water, high ash challenges of Indian coal-fired plants.

There are a few other interesting markets emerging – Indonesia could be a large market but will be challenging in terms of economics and local administration. South Africa should have a current market for flue gas cleaning but has pressing issues with security of supply, water availability and economics which may delay the market somewhat.

There are many emerging markets for pollution control equipment. However, in order to break into these markets, commercial companies will have to look at each country individually to evaluate the challenges each presents and to map out potential routes forward to ensure that their technology is seen as desirable and affordable.

6 Conclusions

The market for emission control technologies is complex, varying with everything from plant-specific issues such as coal quality to the politics and economics of the country in which the plant is situated. Thus, there are no simple guidelines in terms of assessing appropriate retrofit pollution solutions in emerging markets. However, understanding the questions better, may eventually lead to clearer answers.

What creates the market? Coal-fired plants must run in an economic manner and so coal plants will only invest in control technologies when it is in their interest to do so. For many plants, the ultimate enforcing factor is legislation. Markets will be strongest where legislation enforces the requirement.

How does the selection process proceed? The stringency of legislation varies from region to region and often varies further depending on plant age, size and the type of coal being fired. A plant manager will therefore have to determine which limits are applicable to the plant and then determine the most cost-effective means of compliance. For example, for some plants, combustion modifications for NOx control will prove sufficient to meet emission limits whereas other plants will be obliged to fit SCR or even a combination of both combustion controls and SCR. Determining which control options are most appropriate at each plant requires an understanding of the coal chemistry as well as the plant configuration and may often require modelling or demonstration projects as part of the technology selection process.

Will all plants comply? For many plants, this is the ultimate question. Plants can receive permission for delay or derogation, but ultimately plants which plan to continue producing power into the next decade will have to comply with relevant emission legislation. In some countries, such as China, tariffs may help plant economics by paying more for electricity from plants fitted with flue gas cleaning systems. In other regions, such as Germany, the UK and the USA, older units, with a limited remaining lifetime, have determined that investment in further pollution control systems is simply uneconomic and older, less profitable plants will continue to close. This effect is difficult to factor into market projections.

Are there plant specific issues? There are many variations in plant design and performance. The ash and sulphur content of coals can have a significant effect on boiler design and on appropriate flue gas cleaning systems. For retrofits, plant specific factors will be evaluated, modelled and tested before large investments are made. Smaller, older plants may have limited footprint space to install retrofit systems. In these situations, modular and/or vertical retrofits (such as WESP) may work best. Alternatively, replacing individual, in series control systems with a single multi-pollutant system may solve this problem. Water availability may affect the selection of sulphur control system, leading to the selection of dryer systems.

What about installation issues? In India and South Africa for example, where power demand exceeds supply, taking a plant offline for a retrofit is economically undesirable. Staggered retrofitting will be required and systems with a shorter installation time may have an advantage. Pre-built and flexible modular systems may be most appropriate at some plants in these regions.

Which countries should be targeted? This is not an easy question to answer. Although tightening legislation indicates a new market for emissions control technologies, the stability and accessibility of this market will vary from region to region. Many western countries are largely in compliance with emission legislation and so the remaining market is in upgrading, maintenance and repair of existing systems. Arguably the American and Japanese markets are the most complete in that most plants already have technologies in place to reduce all legislated emissions or have plans to install such systems in the near future. The main EU market is relatively complete for particulate, SO_2 and NOx control but there is a new emerging market for mercury control. Since most plants already have flue gas systems in place, the market is most likely to need polishing technologies – oxidants and sorbents to work with existing systems to reduce mercury as an enhanced co-benefit effect. New and potential EU members such as Poland, Romania, Bulgaria and Turkey, have plants which will have to install SO_2 and NOx control systems as part of their accession requirements. Although many of these plants will follow the standard route of installing several control technologies in sequence, these could be potential markets for more advanced multi-pollutant control systems. Funding would, of course, be an issue.

The Chinese market is large, but much of it favours home-produced technologies. New investors into the Chinese market will benefit from working within the Chinese frame of operation, possibly through a Chinese host, to take advantage of local advantages for market infiltration. The emerging Indian market will be the largest globally but faces numerous challenges in terms of lack of finance and expertise. Over and above challenges such as water issues, coal quality issues and the fact that power demand exceeds supply, mean that retrofitting will have to be planned and timed to ensure consistency of supply to the grid. The sheer scale of the market in India suggests that there is a great opportunity for international companies. However, Indian coals have higher ash content than most other coals and many technologies simply have no demonstrated experience in this area. The Indian government wishes to promote Indian-produced technologies. However, there are currently few, if any, Indian manufacturers or suppliers of flue gas control systems. Since relevant expertise and skills are scarce, now is the time for international companies to move into India to set up national franchises to be in place as and when the market establishes.

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