The emerging market for mercury control

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Preface

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

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

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

Abstract

Legislation for mercury control for coal-fired power plants is emerging in several regions. The US Environmental Protection Agency (US EPA) has several new rules, including MATS (the Mercury and Air Toxics Standard, 2014) and CSAPR (the Cross-State Air Pollution Rule, 2011) both of which will have a significant impact on coal-fired power plants in terms of retrofitting control technologies for compliance. Canada has the Canada-Wide Standard which sets caps on mercury emissions for individual Provinces. Although the EU has not yet set emission limits for mercury from coal-fired plants, the new IED (Industrial Emissions Directive) has annual monitoring requirements for mercury emissions. Further, the new BREFs (best available technology reference documents) include details on options for mercury control. This would imply that, although mercury is not currently being regulated, emissions are being monitored and control may be required at some sources in future. China's latest Five-Year Plan (12th Plan, 2011-15) includes emission limits for mercury which, for the moment, are not particularly challenging. However, there is clearly a recent and significant move in China towards the cleaning up of emissions from the coal sector.

In addition to mercury-specific policies and approaches, these regions have other policies and regulations which could have a significant effect on mercury emissions. Looking ahead, based on the consideration that regulations will be enacted for several pollutants simultaneously in these regions, the outlook for environmental equipment regulations with respect to trace element emissions is investigated. The report covers:

- legislative approaches in the different regions;
- suitable control technologies – co-benefit approaches, mercury specific technologies and multi-pollutant strategies; and
- summaries of action in each of the target regions.

Acronyms and abbreviations

ACI	activated carbon injection
BAT	best available technology
BAT-AEL	best available technology – associated emission level
BEP	best environmental practice
BREF	best available technology reference document
BRANN	Bayesian regularised artificial neural network
BTU	British thermal unit
CCC	Clean Coal Centre
CCME	Council of Canadian Ministers of the Environment
CEM	continuous emissions monitor
CERI	Clean Energy Research Institute, China
CFBC	circulating fluidised bed combustion
COMET	Cormtech oxidised mercury emission technology
CSAPR	Cross-State Air Pollution Rule, USA
CWS	Canada Wide Standard
DBD	dielectric barrier discharge
EB-FGT	electron beam flue gas treatment
ECO	electrocatalytic oxidation
EEA	European Environment Agency
ELV	emission limit value
EPRI	Electric Power Research Institute, USA
EPS	Eco Power Solutions
ESP	electrostatic precipitator
EU	European Union
FF	fabric filter (baghouse)
FGD	flue gas desulphurisation
HELCOM	Helsinki Commission Programme
HELE	high efficiency low emission
HES	high efficiency system
ICAC	Institute of Clean Air Companies
ICR	Information Collection Request, USA
IEA	International Energy Agency
IED	Industrial Emissions Directive
IPPC	Integrated Pollution Prevention and Control Directive
LCPD	Large Combustion Plant Directive
LRTAP	Long Range Transboundary Air Pollution (Convention)
MACT	maximum achievable control technology
MATS	Mercury and Air Toxics Standard, USA
MEP	Ministry of Environmental Protection, China
MP-AQC	multipollutant-air quality control
PEESP	plasma enhanced electrostatic precipitation
PM	particulate matter
POG	process optimisation guidance
ppm	parts per million
PRB	Powder River Basin
SCR	selective catalytic reduction
SDA	spray dry absorber

SNCR	selective-non catalytic reduction
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US EPA	United States Environment Protection Agency
WESP	wet electrostatic precipitation
WHO	World Health Organisation

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1 Introduction

Legislation on emissions to air from coal combustion has been tightening for decades. The more developed regions of the world have strict restrictions on emissions of particulates, SO_2 and NOx and some have legislation relating to halogens, organic species, trace elements, fine particulates and even, potentially, CO_2. Legislation for mercury control is recent but has arrived with a sense of urgency due to the relatively rapid increase in atmospheric emissions in the last few decades, a result of its longevity in the atmosphere and ability to disperse globally. Mercury contamination can lead to some fish becoming unsafe for human consumption, especially for pregnant or breastfeeding women as the developing brains of infants are most susceptible to potential neurological effects. The United Nations Environment Programme (UNEP) has established the Minamata Convention on mercury and, once ratified, this legislative instrument could create significant impetus for mercury control worldwide.

This report concentrates on legislation for mercury control in Europe, North America and China and the resulting developing markets for mercury control technologies. Certain forms of mercury are soluble and relatively easy to capture on absorbent materials and so some technologies which reduce emissions of particulates, SO_2 and NOx can also reduce emissions of mercury. These are known as co-benefit effects. Most countries with emission regulations target many different pollutants with a variety of separate policies and so it is a challenge to identify the modifications to plants and the related expense which can be associated specifically with mercury legislation Therefore, as much as possible, this report reviews mercury specific legislation in the target regions but also includes legislation which will affect mercury emissions and the decisions associated with selecting the most appropriate reduction technologies and strategies.

Previous reports by the IEA Clean Coal Centre (CCC) have reviewed mercury legislation in different regions and the control technologies being developed to control them (Sloss 2008, 2009, 2011, 2012; Carpenter, 2013). This report builds upon this information, focusing on current and potential future retrofitting and modifications to the existing coal fleet in these regions as a result of mercury control requirements.

2 Legislative approaches

A previous report from the CCC (Sloss, 2012) reviewed the international and national legislation and standards for mercury control in great detail and the interested reader is recommended to download this report from our website www.iea-coal.org for further reference. This chapter summarises the most relevant information on legislation to reflect how it can affect the control technology marketplace.

There are numerous legislative approaches to reduce emissions from the coal sector. These can range from anything from restrictions on fuel use and minimum efficiency requirements, through cap and trade schemes and reduction targets, to specific emission limit values. Many of these legislative requirements for the coal sector do not relate directly to mercury emissions but will have a significant effect on emissions. As will be discussed in more detail in Chapter 3, techniques used to reduce emissions of other pollutants, such as particulates, SO_2 and NOx, can have a significant effect on mercury emissions though co-benefit effects. And so all relevant legislation must be considered here.

2.1 Fuel use and combustion efficiency

There are few if any forms of legislation which currently relate directly to requirements for fuel use and combustion efficiency. Government policy in some regions, however, may support one fuel over another as a means to promote energy security and sustainability of supply and this, in turn, will affect the proportion of coal use in comparison with gas, oil, nuclear and renewables. Cost and fuel availability are also important factors. Those countries which are moving away from coal to alternative fuels will obviously see a concomitant reduction in emissions of all pollutants from the sector, including mercury, as a result. International legislation such as the UNFCCC (United Nations Framework Convention on Climate Change) and instruments such as the UNEP LRTAP (Long Range Trans-boundary Air Pollution) and Geneva Conventions require reductions in pollutant emissions. Although they do not necessarily relate to coal combustion directly, these conventions influence how governments make decisions on emission standards for coal as they work towards lowering emissions of all relevant pollution in compliance.

Combustion efficiency is something that, once maximised, provides many benefits to a plant in terms of both output and in the reduction of emissions. As plant design improves towards higher efficiency lower emission (HELE) goals, the average emissions of all pollutants should decrease as less fuel is required to produce the energy required. There is little or no legislation relating to minimum plant efficiency. However, policies exist in many regions which promote the prioritisation of plants which are of greater efficiency. Further, much of the tightening legislation seen in the EU and the USA is causing older plants to close or fuel switch as it is simply not economic for operators to invest in expensive bolt-on flue gas treatment systems to extend the plant's operating lifetime. In China, the current Five-Year Plan (12th Plan, 2011-15) requires the removal of older, dirtier coal plants as new, more efficient plants are brought online.

The move to new, cleaner plants will also potentially promote a technology leap in some areas where older plants with little or no emissions control can be replaced with efficient plants with state-of-the-art, multi-pollutant emission control systems.

And so it can be argued that, although there may be no legislation which pertains directly to the amount of coal used in a national budget, nor to the efficiency of the plants firing the coal, the general trend of tightening legislation on all emissions along with environmental policies which promote more clean and efficient fuel sources, means that older, dirtier units are coming offline and being replaced with cleaner and more efficient units. And this, as a result, will mean a reduction in emission factors for all pollutants, including mercury, on a $\mu g/m^3$ per GWh basis.

2.2 Emission ceilings and reduction targets

There are numerous international treaties and conventions which aim to reduce the international transport of pollution around the globe. These instruments will coordinate action between countries to achieve an overall reduction in emissions internationally. For example, the Geneva Protocol sets emission ceilings for SO_2 and NOx. Some countries may choose to comply with this legislation by installing controls for SO_2 and NOx on coal-fired plants and this, in turn, will have a co-benefit effect by reducing mercury emissions. Other conventions, such as LRTAP, HELCOM (Helsinki Commission Programme) and the Binational Toxics Strategy between Canada and the USA, all aim to reduce the movement of trace elements, especially mercury, into the atmosphere but do not specify how these reductions should be achieved (Sloss, 2012).

Countries are unlikely to set emission standards for coal-fired plants based on any single international convention alone, rather they will include the requirements of these conventions alongside other national and international emission reduction requirements when establishing legislation for coal-fired units.

The new Minamata Convention, produced by UNEP and signed by over 100 supporting countries in February 2013, aims to reduce emissions of mercury globally. The convention, which has not yet been ratified, includes requirements for '*mercury control and, where possible, reduction*' from sources including coal combustion. The Minamata Convention does not currently set specific reduction targets for mercury. However, signatory countries are given the option of various approaches for mercury reduction including reduction targets (Sloss, 2012). How these are translated into national policies and whether this will result in new or stricter emission limits for mercury in some regions remains to be seen.

The Canada-Wide Standard (CWS) is currently the only national legislation which sets emission ceilings or caps for mercury. This is discussed more in Chapter 6.

2.3 Emission limit values, ELVs

Emission limits (ELVs) are usually defined in terms of output of a pollutant from the flue gas, either as ppm, $\mu g/m^3$, lb/Btu or in whatever format the local or national units are set. ELVs can be challenging, establishing limits which can only be met with the installation of control devices. ELVs can also be somewhat flexible, in that the means of reaching the limit is not defined – the plant operator can select whichever control approach is most appropriate and, perhaps more commonly, which is most cost effective. For example, ELVs for sulphur could be reached by fuel switching to lower sulphur coal, in some cases, avoiding the need to install more costly emission control technologies. However, ELVs are often set such that they can only be achieved if state of the art control technologies are used.

Table 1 shows a summary of comparative emission limits for major pollutants and mercury in China, the EU (European Union) and the USA.

Table 1 Emission limits in China, the EU and USA, µg/m^3

		China	EU	USA
SO_2	New plants	100	200	160
	Existing plants	200/400	400	160/640
NOx	New plants	100	500/200	177
	Existing plants	100/200	500/200	117/160/640
PM	New plants	30	50	22.5
	Existing plants	30	50	22.5
Mercury	New plants	0.03	No limit	0.001
	Existing plants	0.03	No limit	0.002

As shown in the Table, ELVs for mercury are only currently defined nationally for coal-fired plants in China and the USA. These will be discussed in Chapters 4 and 6 respectively. However, since control technologies used for the control of particulates, SO_2 and NOx can also reduce mercury emissions through co-benefit effects, ELVs for these species are relevant to the potential reduction of mercury emissions from the coal sector in countries where these ELVs are applied. And so, although the EU does not have emission limits for mercury as yet, the emission limits for SO_2 and NOx require the installation of control technologies that will result in mercury reduction as a co-benefit.

The BAT/BEP working group of the new UNEP Minamata Convention is drafting guidelines on how to establish ELVs (emission limit values) and how to create national action plans for mercury reduction. This will be available for those nations who choose to go down these routes as part of their emission reduction strategy under the convention, once it is ratified.

Although no other countries have set strict emission limits for mercury from coal-fired power plants, this does not mean that other legislation based on emission limits does not exist. For example, Germany and the Netherlands appear to be setting mercury specific legislation on new plants on a case-by-case basis. It is unclear whether this is due to specific challenges at these plants or in the location of these new plants or whether this is indicative of potentially tightening requirements on all new plants. There is nothing published to provide further information on this.

In Japan, environmental legislation is also set on a plant-by-plant basis. With heavy emphasis on social responsibility and public credibility, Japanese utilities tend to take pride in being clean with the majority, if not all, plants in the country being fitted with FGD and SCR systems (Sloss, 2012).

The republic of South Korea has a non-challenging mercury emission limit for all industrial facilities of 5 mg/m^3. This limit can be met by almost any plant with a particulate control system. However, most plants are installed with FGD and SCR and are therefore emitting mercury at orders of magnitude below this limit.

2.4 BAT/MACT

Best available technology (BAT) and maximum achievable control technology (MACT) are relatively synonymous terms used to define the most appropriate means of reducing emissions of a certain pollutant. In some cases BAT and MACT may have economic considerations which will allow the exclusion of techniques which, although effective, are too expensive to be applicable in certain situations.

In legislative terms, specifying BAT/MACT as required can be a cost-effective approach as the legislation does not have to be updated when new and improved control technologies come into the market place.

The definition of BAT/MACT can be relatively simple for some pollutants. For example, for particulate emission, ESP (electrostatic precipitators) and baghouses (also known as fabric filters (FF)) are generally accepted to be BAT/MACT. Switching to low sulphur coal or the retrofitting of wet or dry FGD (flue gas desulphurisation) are regarded as BAT/MACT for SO_2, depending on the specific requirements of the legislation. For NOx, BAT can be low NOx burners, SCR (selective catalytic reduction) or SCNR (selective non-catalytic reduction).

Determining BAT/MACT for mercury is not so simple. As discussed in previous CCC reports (Sloss 2008, 2009, 2011), there is no single BAT/MACT for mercury. This is more due to legal/economic concerns than to defining the technology. For a developed region which wishes to lower emissions by >90% mercury then the BAT/BEP options are likely to be oxidant or sorbent based at many plants. Conversely, if an emerging economy wishes to reduce mercury emissions by, say, 50% in the most cost-effective way possible, then efficiency, fuel-switching and co-benefit effects may be more appropriate. The definition of BAT/MACT must be qualified with the amount of control required in order for the decision process to be simplified.

Mercury behaviour and control can vary significantly with coal type and combustion conditions. There are numerous options for mercury control ranging from enhanced co-benefit effects through to mercury specific techniques such as oxidants and sorbent, electrochemical methods and multi-pollutant control systems. The options for BAT/MACT for mercury are much more varied and so determining which approach is most appropriate at each plant is far more challenging for plant operators than deciding how best to control, say particulate matter. The market for mercury control is new and still evolving and so options to be considered as BAT/MACT for mercury are still emerging. This will be discussed in more detail in Chapter 3.

The EU is currently preparing BAT reference documents (BREFs) which outline the various processes available for mercury control at coal-fired plants (*see* Chapter 5). For the moment, there is no EU legislation which applies to mercury control in Europe and so these BREFs are often taken as an indication that, perhaps, legislation for mercury is being considered. However, since the current legislation for coal plants in the EU is on a site-specific permit basis, taking into account national and local considerations, the BREFs will be useful for any plants which are given unique requirements for mercury control. There is some indication that this may be the case for a few new coal plants in Germany and the Netherlands, although there is no published literature available to confirm this.

The UNEP Coal Partnership, as led by the IEA CCC, is working with selected international experts to produce BAT/BEP guidelines for the coal sector under the new Minamata Convention on mercury. The BAT/BEP document is in early stages of production as this report goes to press but is currently based on the same format and information as was in the POG (process optimisation guidance) document, discussed in Section 3.5. This information has been updated and expanded with more information relating to improving plant performance in general (BEP requirements) plus additional information on BAT for industrial coal-fired facilities. The aim of the BAT/BEP document is to provide as much information on the options available for mercury control without being prescriptive. The convention recognises challenges for some countries with respect to economics, geography and other location-specific variables. The guidance therefore aims to provide enough information for an informed decision to be made.

The BAT/BEP working group hopes to collate a selection of case studies on mercury control which represent the different options for mercury reduction so that parties may learn from experiences elsewhere. This would include everything from front end changes in fuel use through to more specific bolt-on control technologies. A steering group will be established to review and select the most appropriate case studies to be included.

It is planned that the BAT/BEP guidance document for coal will be published for public consultation early in 2015 with a view to the refined draft being available for discussion at INC7, the 7th round of the international negotiating committee for Minamata. There will then be a refined draft available to be discussed after the Convention is ratified.

2.5 Comments

There are many ways of achieving emission reductions from the coal sector including everything from policies that promote energy efficiency, through emission ceilings and caps, to stringent emission limits and specific requirements for bolt-on flue gas treatment systems. At the moment, there is little that refers directly to mercury emissions, outside North America and China. However, there are many existing policies which relate to emissions of other pollutants, such as particulates, SO_2 and NOx which have a co-benefit effect of reducing mercury emissions. This means that, during the development of mercury specific legislation, existing co-benefit effects from other legislation should be taken into consideration.

The new UNEP Minamata Convention on mercury has not yet been ratified. However, the convention does have the potential to catalyse new national legislation on emissions in some regions. At the moment, the convention merely recommends that countries choose the most appropriate methods for mercury reduction, listing the options as reduction targets, emission limit values and BAT/BEP approaches.

3 Control technologies

As discussed in previous IEA CCC reports (Sloss, 2008, 2009, 2012), the behaviour of mercury in coal combustion systems is highly variable, changing with coal characteristics, boiler type and operation, the presence of other pollutants, and the application of air pollution control devices. The choice of control technology is therefore not simple and the decision is commonly made on a unit-by-unit basis taking all of the variables into account. There is a section at the end of this Chapter which provides guidance on the decision making process. The sections below summarise the different control technologies and techniques which are applicable to mercury and, where possible, give guidance on where these are most suitable.

There are three essential steps to mercury control at coal-fired plants (Looney and others, 2014):

- elemental mercury must be converted to oxidised mercury;
- the oxidised mercury must make contact with a medium (solid or liquid) which will remove it from the gas stream; and
- it must be captured and sequestered effectively and securely by that medium for removal from the plant

So that:

Conversion efficiency x contact efficiency x capture efficiency = overall mercury control %

The options for mercury control below take advantage of one or all of these steps.

3.1 Co-benefit

Co-benefit control refers to any emission reduction achieved by methods or control systems which have been applied for the control of other pollutants, as in mercury removal achieved by systems installed to control particulates, SO_2 or NOx, such as:

- particulate controls – electrostatic precipitators (ESP), baghouses (also known as fabric filters, FF);
- flue gas desulphurisation (FGD) for SO_2 control; and
- selective catalytic reduction (SCR) for NOx control.

The effect of these control systems on mercury emissions, and how this effect can be maximised, is discussed in the sections to follow. There is also information on approaches such as fuel treatment and improvement of overall plant operation efficiency, which can reduce mercury emissions in some situations.

3.1.1 Efficiency and coal improvements

The simplest way to reduce emissions from coal combustion is to stop burning coal through **fuel switching**. Older and/or less efficient plants which are finding compliance with increasingly stringent emission limits too expensive may close or may be refitted to fire gas instead of coal. In these instances, the emissions of mercury disappear from the inventory. But in some situations, coal switching and blending can be a better option.

The choice of coal or coal blend can be manipulated to ensure that mercury capture in downstream pollution control devices is as effective as possible. Coal which is inherently high in halogens (such as chlorine and bromine) will naturally produce more mercury in the easy to capture oxidised form. For this to be effective as a control option, the coal chlorine content should be quite high (producing 500-2000 ppm chlorine in the flue gas) (Trovant, 2013). Coals or combustion conditions which produce high unburnt carbon content may also help enhance mercury capture in the solid form. However, unburned carbon is often a sign of inefficient combustion and can affect fly ash sales and so is not always something a plant operator is willing to promote.

High sulphur coals can interfere with mercury oxidation and can also reduce mercury capture in coal ash and any sorbents being used for mercury control (*see* Section 3.2) and so this must be taken into account if considering a change in coal.

It is theoretically possible for a plant to have a compliance strategy which is based on switching to low-mercury coal. However, the coal would also need to be low in sulphur and, possibly, chlorine, to comply with other emission limits. This is unlikely to be used as a long-term option at many full-scale plants but could be considered as an interim or short-term strategy until a more long-term solution was found. Trovant (2013) notes that there could be a surge in demand for unique coals with low mercury in some regions. Trovant (2013) has ranked different US coals according to their mercury behaviour profiles. Appalachian region bituminous coals tend to be high chlorine and low sulphur, thus producing more oxidised mercury than interior province bituminous coals, which are higher sulphur and slightly lower chlorine. PRB (Powder River Basin) and western/Gulf coals are low in both chlorine and sulphur and therefore do not provide optimal mercury speciation for easy control.

Chen and others (2014) have reviewed the data on coal use and coal mercury content which are commonly used to estimate emissions from coal combustion in different regions. They concluded that, if the mercury content in locally produced fuels is used to estimate emissions, then the resulting global mercury emissions from coal use may be overestimated by 4.7%. This is because of the increasing international trade of coals – most power plants are no longer dependent on local indigenous coals and can now look to the international market to buy cheaper and often cleaner coals from elsewhere. For example, Australia and Indonesia produced 324 and 260 Mt coal, respectively, in 2007 and both exported 75% of what they produced. Japan, on the other hand, imported all of the 187 Mt of coal that it consumed in 2007 (no more recent data were given). The mercury contents of these coals in different regions vary significantly. The mercury contents of coals in major exporting countries such as Indonesia and Vietnam are generally lower than the global averages and therefore international trading has led to a reduction in the average content of mercury in coal and thus a concomitant reduction in mercury emissions.

The increased availability of different coals on the international coal market also means that more and more plants can consider the option of **coal blending** for mercury control. A previous report from the

CCC (Sloss, 2014a) looked at coal blending, concentrating on where it is happening and what can be achieved. The report suggested that coal blending for mercury reduction is unlikely to be considered as a viable option unless there are other benefits to coal blending, since the costs of changing coal mixes can be high. Travoulareas and Jozewicz (2005) considered coal blending and cofiring as a potential method for multi-pollutant control and concluded that its applicability would be on a case by case basis. Coal blending could add capital costs of 20–100 $/kW, fuel switching up to 200–300 $/kW and cofiring of 30-200 $/kW. They emphasised that changes in coal characteristics could result in significant issues in plant performance, including potential slagging and fouling. Therefore switching coals at a plant would not be considered as a valid mercury control option unless the new coal or coal blend did not incur expensive modifications to the coal handling and processing nor any detrimental effect on plant performance.

Coal cleaning can be a multi-pollutant control strategy as removing ash and incombustible materials increases the efficiency of combustion. Coal cleaning for sulphur removal has been shown to concomitantly remove mercury since mercury is often associated with the pyrite in coal. Coal cleaning can remove mercury by between 18–79% in some coals (Zajusz-Zubek and Konieczynski, 2014). However, the information in the literature suggests that the majority of mercury-based coal-cleaning studies are academic. There is no published information of the practical application of coal cleaning for this although the K-Fuel system does use coal cleaning as part of its mercury control strategy. K-Fuel is a beneficiated coal produced from PRB or lignite by physical separation followed by thermal processing. During the thermal processing stage mercury is removed and captured in a carbon-bed adsorption reactor (Travoulareas and Jozewicz, 2005). Although the process looked interesting, it would seem it ran into technical issues and no further developments have been made since (Wikinvest, 2009).

3.1.2 Particulate control systems

A small fraction, generally less than a few per cent, of mercury can be found in the flue gas of a coal-fired plant in the particulate form. The majority of mercury is gaseous. But oxidised mercury can bind to particles as they cool especially if they have an adsorbent surface present, such as unburnt carbon; and so some mercury can be captured by particulate control systems, although the total capture will be very coal and condition specific.

Table 2 shows the mean mercury emission reductions achieved in different air pollution control device combinations in coal-fired power plants in the USA. This is based on actual plant data collected during the US EPA’s (United States Environment Protection Agency) Information Collection Request (ICR) where all large coal-fired units in the USA were required to provide monitoring data on mercury in coal and mercury emissions from the stack. The table considers various combinations of pollution control devices such as PM (particulate matter) systems (ESP and FF), FGD, spray-dry absorbers (dry FGD systems), and SCR.

Table 2 Mean mercury emission reduction for pulverised coal-fired boilers (Travoulareas and Jozewicz, 2005)

Emission control System		Average Hg reduction, %		
PM control only	ESP – cold side	35	3	0
	ESP – hot side	14	12	not tested
	Fabric filter (FF)	89	73	not tested
	Particulate scrubber	12	0	33
PM and spray dry absorber (SDA)	ESP and SDA	not tested	50	not tested
	FF and SDA	98	23	17
	FF and SDA and SCR	97	not tested	not tested
Pm control and wet FGD system	cold side ESP and FGD	81	30	42
	hot side ESP and FGD	45	25	not tested
	FF and FGD	97	not tested	not tested
	FF and FGD	97	not tested	not tested

As the table shows, FF are generally more effective at capturing mercury than ESP systems. This is due to the increased residence time between particles, which contain unburned carbon and other species with adsorptive properties, and the oxidised mercury in the flue gas. ESP systems are moderately effective for capturing mercury, as the cold-side systems provide greater capture than hot side systems due to the reduced volatility of mercury in the colder system. The effectiveness of any particulate control system for mercury increases with the amount of mercury in the oxidised form, since oxidised mercury is 'stickier' and more soluble. Coals such as bituminous coals tend to produce more mercury in the oxidised form that lower grade coals and lignite. This is thought to be due, amongst other things, to the increased presence of halogens and other species which have oxidising properties.

The data shown in Table 2 give only the average mercury reduction with different coals and pollution control systems. The ranges can be significant and so the table should only be used as a guideline and not as a guarantee.

3.1.3 NOx control systems

NOx can be controlled from coal-fired plants by two distinct approaches:

- low NOx burners within the combustion zone;
- SCR/SNCR – downstream flue gas treatment systems.

The positioning of burners within the combustion zone can significantly affect the fuel to oxygen ratio during combustion which, in turn, affects the stoichiometry of N_2 to NOx reactions. By ensuring more complete combustion, such as with additional burners (over-fire air), the majority of nitrogen from both the combustion air and the fuel will leave the combustion zone as N_2 rather than as NOx. Although this does not affect mercury emissions directly, it is not uncommon for low NOx burners to result in an increase in unburned carbon in ash which can, in turn, help to capture mercury emissions in the particulate control devices. However, plant managers are not likely to manage the level of unburnt carbon as a means of mercury control but are rather more likely to maximise the combustion efficiency to reduce unburned carbon, the presence of which can have a detrimental effect on fly ash sales.

SCR systems for NOx control involve a layer of oxidant to oxidise NO_2 in the flue gas. It has been well established that these catalysts can also oxidise elemental mercury and thus enhance mercury capture in any downstream control device. However, over months of use, mercury can reduce the effectiveness of catalysts, lowering the NOx reduction rate. Systems such as COMET (the Cormtech oxidised mercury emissions technology) are being marketed which characterise SCR reactor performance and determine the correct catalyst formation for maximum NOx and Hg control. Catalyst performance can be enhanced by halogen injection and by efficient management of the time period between catalyst surface replacements (Bertole, 2013). As mercury control becomes more importance in some regions, SCR catalysts will be developed and employed with a dual function – to control both NOx and mercury simultaneously.

SNCR (selective non-catalytic reduction) for NOx control has not been reported to affect Hg emissions and so is not discussed further.

3.1.4 SO_2 control systems

As shown in Table 2, wet FGD and dry scrubber systems for SO_2 can have a significant effect on mercury emissions, especially for bituminous coals. Wet FGD systems are by far the most popular method for sulphur control on large coal-fired boilers worldwide which is useful since mercury can also be captured effectively in most FGD systems. The legislation in place for SO_2 control in North America, the EU and China means that the majority of large coal-fired units will have FGD in place before the end of this decade. This will guarantee a significant reduction in mercury emissions through co-benefit effects (Sloss, 2009; *see* also Chapters 4, 5 and 6).

Looney and others (2014) have reviewed the efficiency of mercury capture in wet FGD systems. They argue that the maximum amount of mercury oxidation by systems such as SCR, halogens and other additive oxidants is 95%. Add to this the maximum theoretical mass transfer limit of 98% contact for a wet FGD (with no bypass), then the maximum mercury capture in a wet FGD system is 95% x 98% which is 93%. Wet FGD systems with a bypass will clearly have lower removal efficiencies. And so, in plants with high mercury content coals, 93% mercury removal may simply not be enough to meet the limits required under the new MATS (Mercury and Air Toxics Rule) in the USA (*see* Chapter 6). 93% removal may be so close to the limit for some plants that they risk being in compliance sometimes but not always. These plants may have to consider additional approaches to ensure compliance at all times. For example, a real-time study using a continuous emissions monitoring system (CEM) at a plant installed with both an SCR and a wet FGD system showed that the plant was out of compliance between 5% and 33% of the time, based on a rolling 30-day average.

Mercury capture in wet FGD may not be complete – some of the mercury may not be trapped permanently in the scrubbing solution but may be re-emitted into the flue gas and ultimately escape from the stack. Additives are being developed which inhibit this re-release of mercury, some of which are based on oxidants such as sodium chlorite which prevent the reduction of mercury back to a form which may be re-emitted from the scrubber. These are discussed more in Section 3.2.1.

SDA (spray drier absorbers) refer to flue gas desulphurisation systems which collect the solid reaction products (from lime slurry or hydrated lime) in a dry form rather than the solution seen in wet FGD systems. SDA systems have been shown to reduce mercury emissions by up to 95% but, as always, this depends very much on the coal type and combustion conditions. SDA systems are not as common as wet FGD systems due to more challenging operating requirements. Spray dry systems have been developed specifically for some circulating fluidised bed (CFBC) systems, such as those offered by Lurgi, Wulff GmbH and FLS Miljo. Mercury removal rates for these systems range from 50–89% (Travoulareas and Jozewicz, 2005).

Alstom have patented the NID™ system, a semi-dry FGD system which reduces mercury emissions by 90%, in addition to controlling SO_2 and PM. The system is being used at the 585 MW Boswell Energy Centre plant of Minnesota Power in Cohasset, MN, USA (Power Engineering, 2013b). The NID technology has also been bought for two 66 MW coal units at the Homer City Generating Station in Indiana County, Pennsylvania and there are now over 60 NID units worldwide (Alstom, 2014a).

3.1.5 Combined co-benefit effects

As mentioned in the Sections above, PM, SO_2 and NOx control technologies can significantly reduce mercury emissions. The maximum amount of mercury control occurs when these three systems are all present. Figure 1 shows the common layout of a modern power plant with retrofitted control technologies for all the major pollutants.

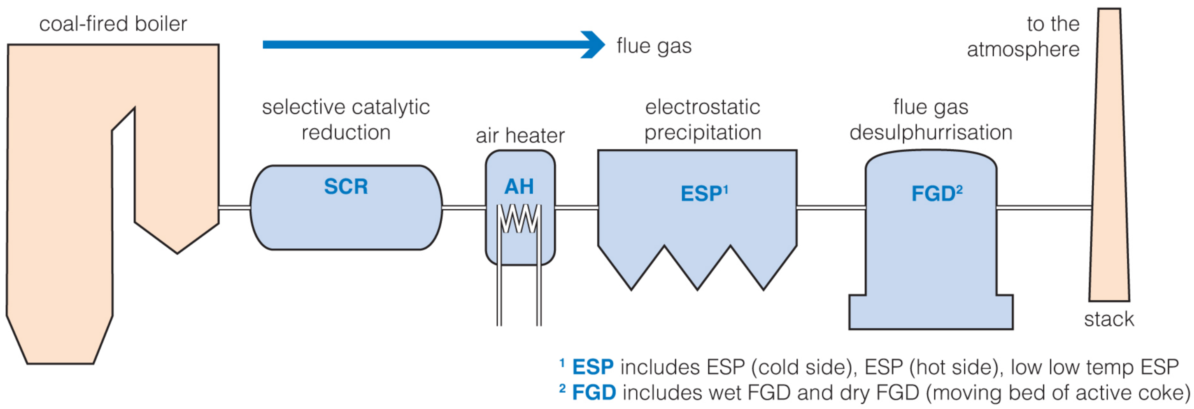

Figure 1 Process diagram of a typical configuration of coal-fired power plant (Moritomi, 2014)

The passage of mercury through the plant therefore allows for some oxidation during combustion (via halogens and other oxidants in the coal), further oxidation in the SCR catalyst, capture of some particulate mercury and also adsorption of oxidised mercury onto trapped particulates in the FGD or baghouse and then finally some more oxidised mercury capture in the FGD system. The combination of these technologies can give significant mercury reduction as shown in Figures 2 and 3. The data shown in these figures relate to emissions from coal-fired plants in Japan but are applicable to similar systems operating elsewhere.

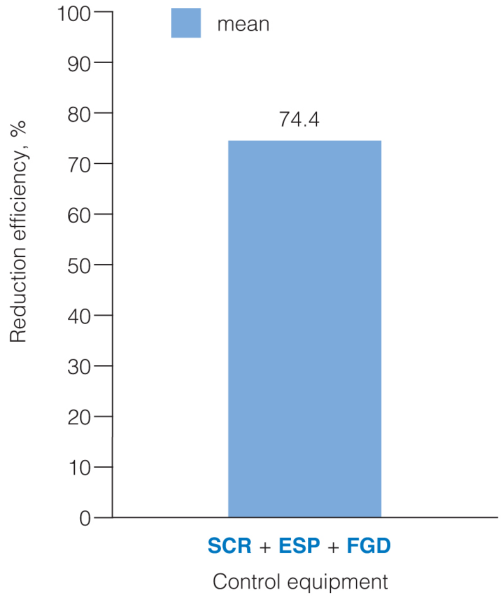

Figure 2 Mean mercury reduction efficiency of coal-fired power plants with SCR+ESP+FGD (Moritomi, 2014)

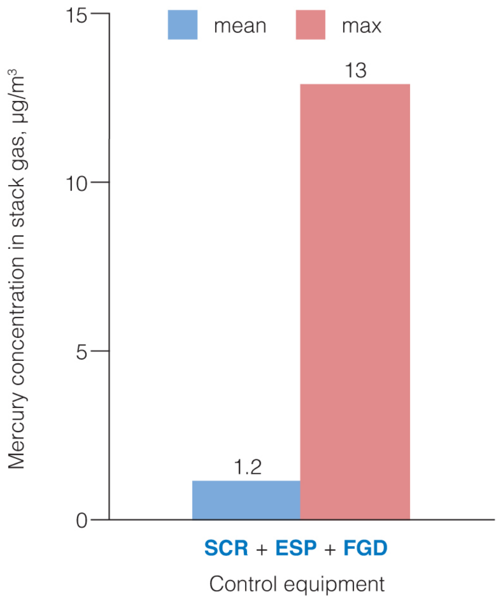

Figure 3 Mean and maximum mercury concentrations in stack gas of coal-fired power plants with SCR+ESP+FGD (Moritomi, 2014)

Again, although these data relate to plants in Japan, the same principle applies to plants with the same format elsewhere (excluding challenging coals). The mean mercury removal is around 75% and the concentration of mercury in the stack gas will be reduced to 1.2–13 µg/m³. When compared with the current emission standards listed in Table 1 in Chapter 2, it is clear that co-benefit effects would be sufficient for compliance in China but may not be adequate for compliance with MATS in the USA.

Flue gas cooling can enhance mercury capture in existing particulate control systems. HES (high efficiency systems) have been designed to extract waste heat from the flue gas to make it available elsewhere in the plant. The HES system is used at plants in the EU and Japan to re-heat scrubbed flue gas in order to eliminate visible plumes. The HES system reduces the temperature of the gas exiting the air heater from 135°C to 90°C by using the cool saturated gas from the FGD system as the cooling medium. This raises the FGD outlet gas temperature from 45°C to 90°C. In addition to other plant benefits, the use of HES can improve the mercury capture in the cooler particulate control system, raising the mercury capture efficiency from 25% to 50% to 50% to 75% (Iwatsuki and others, 2008).

3.2 Mercury-specific approaches

It is actually quite difficult to completely separate mercury-specific approaches from other methods which result in mercury control. The co-benefit mercury reduction achieved in particulate and FGD systems, as discussed above, can be enhanced with chemical treatments and plant modifications but that does not re-define the existing system as a mercury-specific control technology. The following sections therefore cover options to specifically enhance mercury co-benefit effects in existing pollution control systems as well as giving details of systems that could be defined as being designed specifically for mercury control.

3.2.1 Oxidants

Since oxidised mercury is easier to capture, many commercial companies are working with solutions and sprays which deliver an oxidant either into the coal feed, into the boiler or somewhere upstream of particulate and sulphur control devices. KNX™ is an oxidant, based on bromine, which is marketed by Alstom. KNX can be added onto the coal or injected into the furnace at the economiser outlet. MercPlus™ is a similar product produced by Babcock and Wilcox. Additives such as MercPlus are particularly suitable for coals which are low in halogens, such as PRB coals. By combining oxidants and activated carbon systems (*see* Section 3.2.2) the mercury removal rate can be maximised (Babcock, 2014). There are many multi-pollutant control systems which incorporate oxidants to enhance not only mercury capture, but NOx control. These are discussed more in Section 3.3.

As mentioned in Section 3.1.3, SCR systems for NOx control can oxidise mercury to make it easier to capture in downstream control devices. It is also possible to install an oxidation catalyst (such as palladium) primarily for mercury control, upstream of a wet FGD unit. There are reported to be a few demonstration studies of technologies of this type but nothing appears to have reached commercial scale.

There are also reagent based systems being marketed to enhance mercury capture in wet FGD. As mentioned in Section 3.1.4, there can be an issue with mercury being captured but then re-emitted from wet FGD systems. Nalco markets a MerControl 8034 product whilst Babcock and Wilcox have Absoprtion Plus (Hg)™. These products work to trap the dissolved mercury in an insoluble form which can be precipitated and removed from the wet scrubber (Carpenter, 2013). Nalco, an Ecolab Company, has applied their MerControl™ Technologies at over 80 different utilities representing over 40 GW of electric generating capacity. Application of Nalco's MerControl technologies achieves mercury reduction greater than 90%, with typical resulting emission rates below 1.0 ug/m^3. All Nalco MerControl Technologies are liquid based, requiring minimal capital investment. Injection systems for MerControl 7895 or MerControl 8034 are typically 50% less than the cost of standard activated carbon injection systems. Figure 4 shows a typical MerControl tank and feed system (Maier, 2014), illustrating how little the oxidation systems disrupt the existing plant layout.

Figure 4 MerControl tank and control system (Maier, 2014)

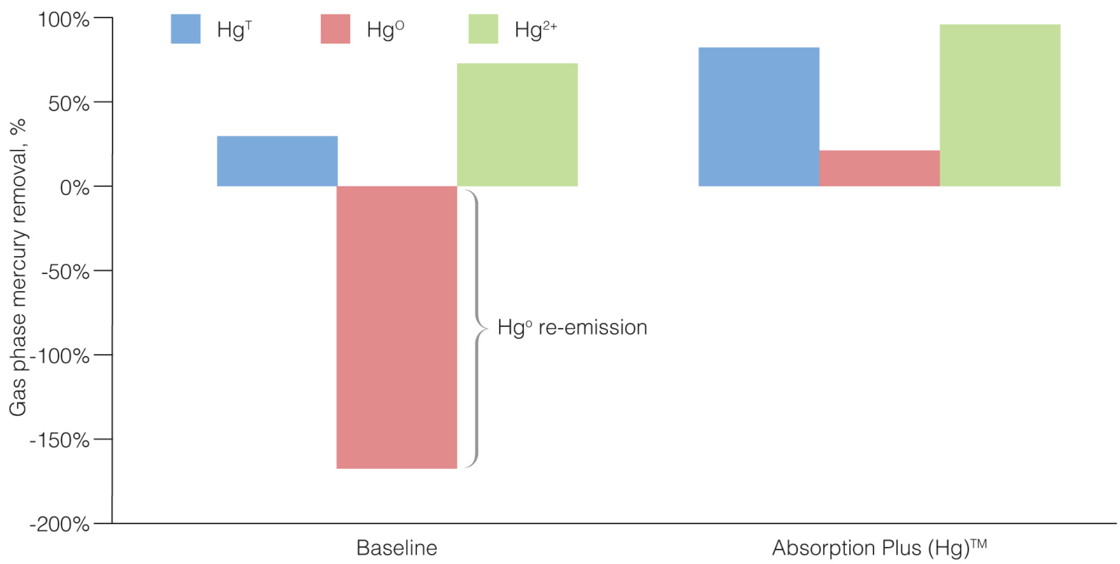

Figure 5 Effect of Absorption Plus (Hg)™ additive on mercury re-emission from a wet FGD system (Babcocks, 2014)

Without the additive, there was significant re-emission of mercury in the elemental form from the FGD system which reduced the overall removal efficiency for mercury. The amount of elemental mercury re-emitted is above 100% due to the conversion of mercury from the oxidised into the elemental form and the re-release of mercury which accumulates over time. With the additive, there is no re-emission of mercury at all. The mercury is trapped in the solid waste recovered from the wet FGD system with no negative effects on the operation of the scrubbers.

Activated carbon can also be used to stop mercury re-emissions from FGD systems. Li and others (2014) report on the use of ADA advanced water powdered activated carbon as the MATS compliance technology at the Sat River Project's Navajo Station Unit 3, AZ, USA.

ADA technologies produce and market Cyclean B, a halogen-based liquid additive that oxidised mercury. The solution is designed to be applicable to PRB and lignite fired cyclone boilers but could be used at bituminous-fired plants. The Cyclean B is used in conjunction with Cyclean A which is a fluxing additive to improve cyclone bottom-slag flow. The mercury reductions reported are >40%. M45 is a similar product to Cyclean but is marketed for CFBC boilers, also reducing mercury emissions by >40% (ADAES, 2014).

3.2.2 Activated carbons and sorbents

Activated carbon injection (ACI) systems have been in development for over a decade for several pollutants including organic compounds and mercury. These sorbents often capture several pollutants, including SO_2 and halogens, and so can also be considered as multi-pollutant techniques. This section will concentrate on sorbents marketed specifically for mercury, and multi-pollutant sorbents will be considered in Section 3.3.

For many plants in the USA, activated carbon meets the MACT requirement. Even before MATS had been finalised, it was already being acknowledged that activated carbon injection was '*expected to be the primary technology of choice for controlling mercury emissions*' (Bustard and others, 2011).

Activated carbons were initially used for water purification and moved into the flue gas cleaning market in a relatively crude form in the mid-1990s. Since then, they have been processed and developed into far more efficient sorbents. New sorbents are being introduced into the market place all the time and the claimed level of mercury capture for these can be over 90%. However, as with all mercury control options, the actual efficiency of mercury capture will be case-specific. And so plants considering using sorbents will test several options on site before making a decision as to which one works best for them. There will also be plant-specific adjustment for the amount of sorbent required to achieve the required level of mercury control. ACI therefore offers a relatively flexible approach with many suppliers knowing that they can guarantee mercury reduction. The hardest plant operator decision in some cases is simply sourcing the cheapest sorbent.

The mercury capture capability of sorbents is increasing at an impressive rate so that, as time goes on, less sorbent material is needed to achieve the same results. This means that published cost and efficiency data can become out of date rather quickly.

As discussed in the recent CCC report (Sloss, 2012), sorbents are being developed with additional properties such as:

- chemically treated activated carbons, with halogens or similar oxidant potential built in;
- combination with alkalis such as magnesium oxide or sodium sesquicarbonate (trona) to reduce the competition for SO_3 for sites on the sorbent surface;
- materials which do not affect fly ash sales due to increases in unburned carbon;
- materials which produce waste materials which can be sold as fertiliser.

An internet search for activated carbon will bring up an ever increasing choice of commercial suppliers such as ADA-ES, Cabot, Nalco, Calgon, Norit, Alstom and Albemarle. Markets are also emerging for non-carbon based sorbents including amended silicates. Chapter 6 gives more information on the activated carbon systems which are dominating the market in North America.

3.3 Multi-pollutant systems

A recent report by the Clean Coal Centre (Carpenter, 2013) gives an excellent review of multi-pollutant control technologies. Travoulareas and Jozewicz (2005) also produced a detailed review of multi-pollutant control systems and the interested reader is referred to these documents for further reading.

3.3.1 Advanced particulate control systems

The Electric Power Research Institute (EPRI) has developed the **TOXECON™** process (Figure 6), a system comprising COHPAC™ (a combination of ESP and baghouse) and sorbent injection. Sorbents can be injected for both sulphur and mercury removal and can therefore be a combination of lime and activated carbon materials, depending on the plant specific requirements. Pilot- and full-scale demonstrations of the TOXECON™ process have been carried out at several full-scale coal plants in the USA, including Comanche, Hudson, Gaston, Pleasant Prairie, Salem Harbour and Brayton Point.

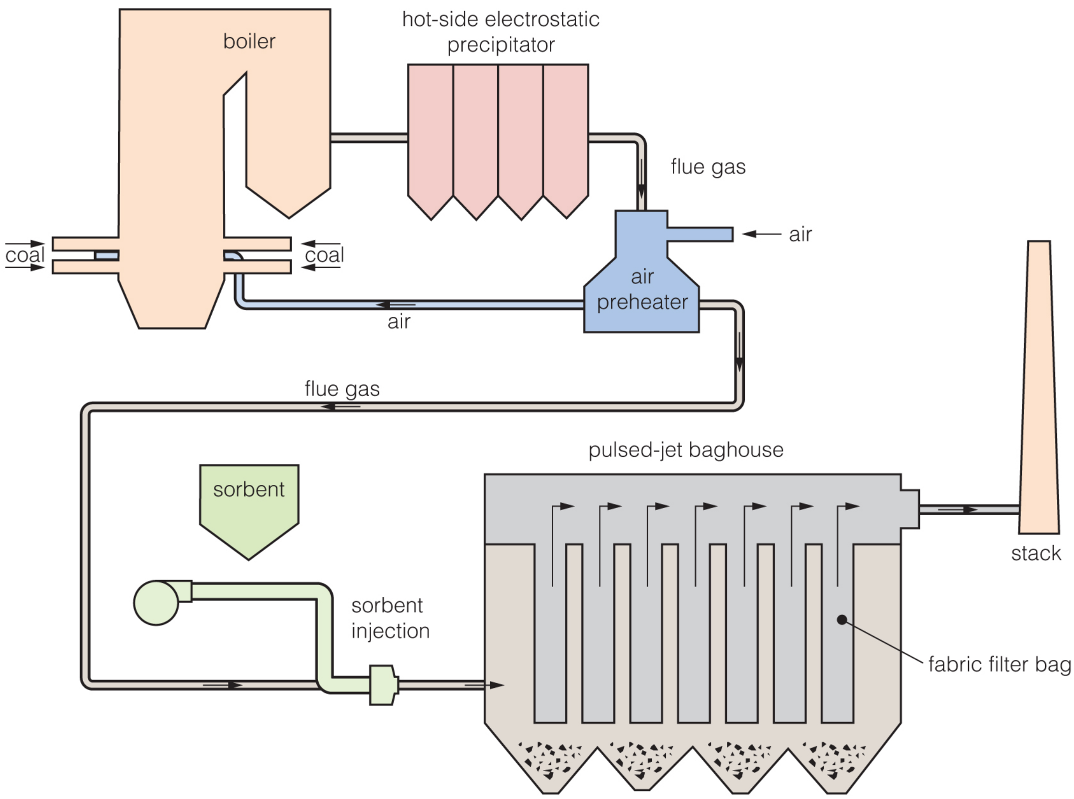

Figure 6 TOXECON™ process

One of the main concerns of the TOXECON™ process is the possible increase of unburned carbon in the fly ash which could negatively affect fly ash sales. Hamon Research-Cottrell has installed over 1700 MW of COHPAC™ technology, on both coal-fired boilers and waste-to-energy incinerators to date (Hamon, 2014).

URS and W L Gore and Associates market the **GORE™** technology, a specially designed particulate control filter system which uses 'mercury control nodules', in a wet scrubbing systems to reduce SO_2, HCl and mercury simultaneously. A pilot-scale demonstration at the Yates power plant in Nerman, GA, USA proved 90% mercury removal over a 6 month test period (Carpenter, 2013). A full-scale demonstration project is under way at the 75 MW Sherco Unit 1 (Carstens, 2014).

Airborne Clean Energy Ltd in Calgary, AB, Canada market the Airborne™ process which combines dry sorbent (sodium bicarbonate) injection with enhanced wet scrubbing and chemical oxidants, claiming over 99% removal of SO_2, NOx and mercury. The system produces granular fertiliser as a by-product. Although the system has not been demonstrated at commercial scale, it has been tested on a 5 MW slipstream at the Ghent station, KY, USA. An application for a permit for a full-scale demonstration in New Mexico was not secured due to issues over CO_2 emissions. Currently the process seems to be moving into the commercial market in China, with two projects under way (Carpenter, 2013).

NeuStream™-MP is a multi-pollutant system based on dual alkali FGD with upstream ozone injection. The system, marketed by Neumann Systems Group, achieves only around 80% mercury removal but significantly higher removal rates for other pollutants. It has been demonstrated at slip-stream scale at the Martin Drake Unit 7 plant in CO, USA and a full-scale system is being installed at Drake Units 6

(85 MW) and 7 (142 MW) (Figure 7). Capital costs are reported to be 50% below that for spray dry scrubbers and operating costs are 40% lower and there should be no detrimental loss of any fly ash sales due to installation of the process (Neumann, 2014)

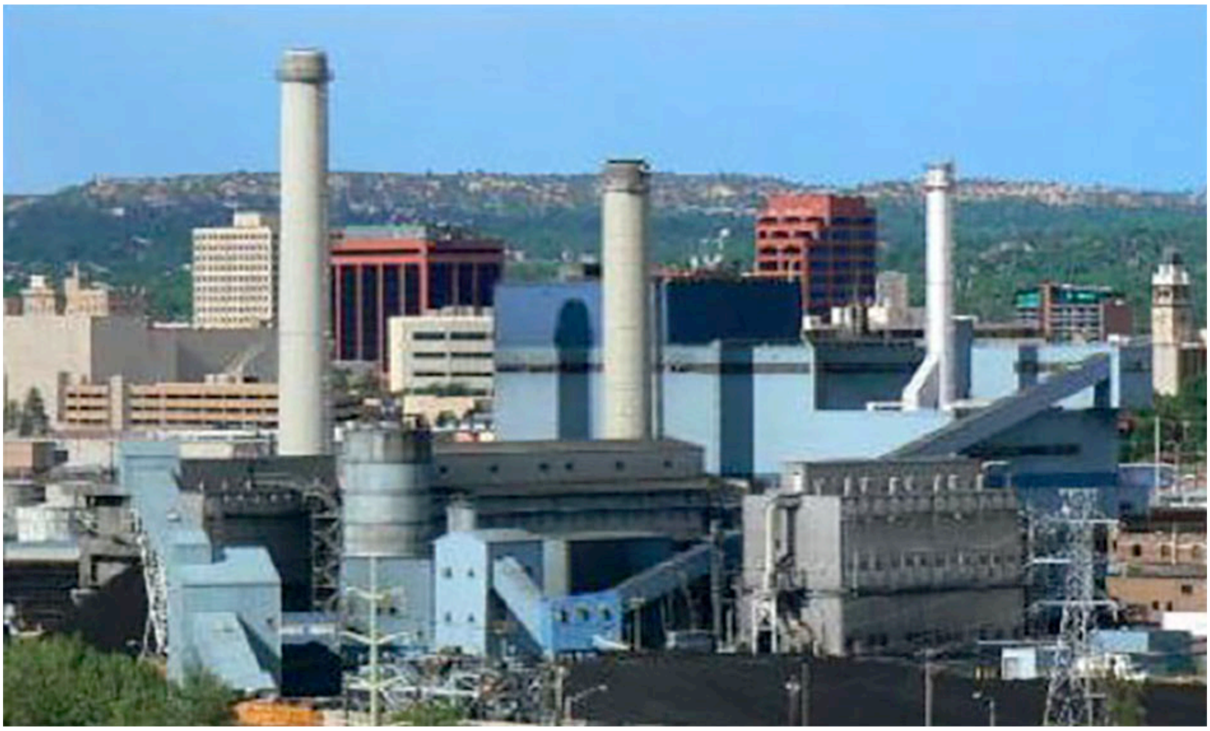

Figure 7 $110 million NeuStream™ plant at the Martin Drake Power Plant, CO, USA (Neumann, 2014)

Skyonic Corporation have developed the SkyMine® process which removes several pollutants, including mercury, from flue gas using sodium hydroxide from brine and produces saleable by-products. 90% mercury removal was achieved at the pilot-scale demonstration at the Luminant Big Brown Power plant in Fairfield, TX, USA. A full-scale demonstration at a cement plant in Texas, USA, should be online sometime during 2014 (Carpenter, 2013).

3.3.2 Catalytic filter systems

The SNRB™ (SOx, NOx, ROx, Box) process was developed by Babcock and Wilcox during the 1970s and 1980s, based on alkali sorbent injection and a high temperature fabric filter. The ceramic bags within the filter contain an SCR catalyst for NOx control. The system was probably effective for mercury control to some extent but little or no data were published on this and the system seems to have not been developed any further. Ceramic or candle filters have also been developed for combined SO_2 and NOx control but, again, there does not seem to have been much published on their mercury control capabilities despite the fact that co-benefit effects would have been virtually guaranteed (Carpenter, 2013).

3.3.3 Advanced and regenerating sorbents

Most of the sorbents discussed earlier are not re-usable. This means they end up as solid waste which must be disposed of and this adds extra cost to plant operators. Many companies are therefore developing sorbents which either do not affect fly ash sales, produce new 'waste' products such as fertilisers, or are actually regenerable and can be used again.

ReACT™ – regenerative activated coke technology – is a multi-pollutant system which can control SO_2, NOx, and mercury in flue gases. The system uses a fraction of the water of wet FGD systems and produces a saleable sulphuric acid product that can be sold for industrial use. Two of the units at the J-Power Isogo plant in Tokyo, Japan, have had a ReACT system installed since 2002 (unit 1) and 2009 (unit 2). Another ReACT system has been installed at the Takehara plant since 1995. The system is based on a dry scrubber via a moving activated coke bed. The Isogo units are 600 MW ultra-supercritical boilers with SCR and ESP systems installed. Isogo has the lowest emission levels of any plant in the world, with SO_2 and NOx emission values in the single ppm range. Mercury removal is well over 90%. The system regenerates itself, as shown in Figure 8. The pollutants are desorbed and collected and the regenerated coke is returned to the system.

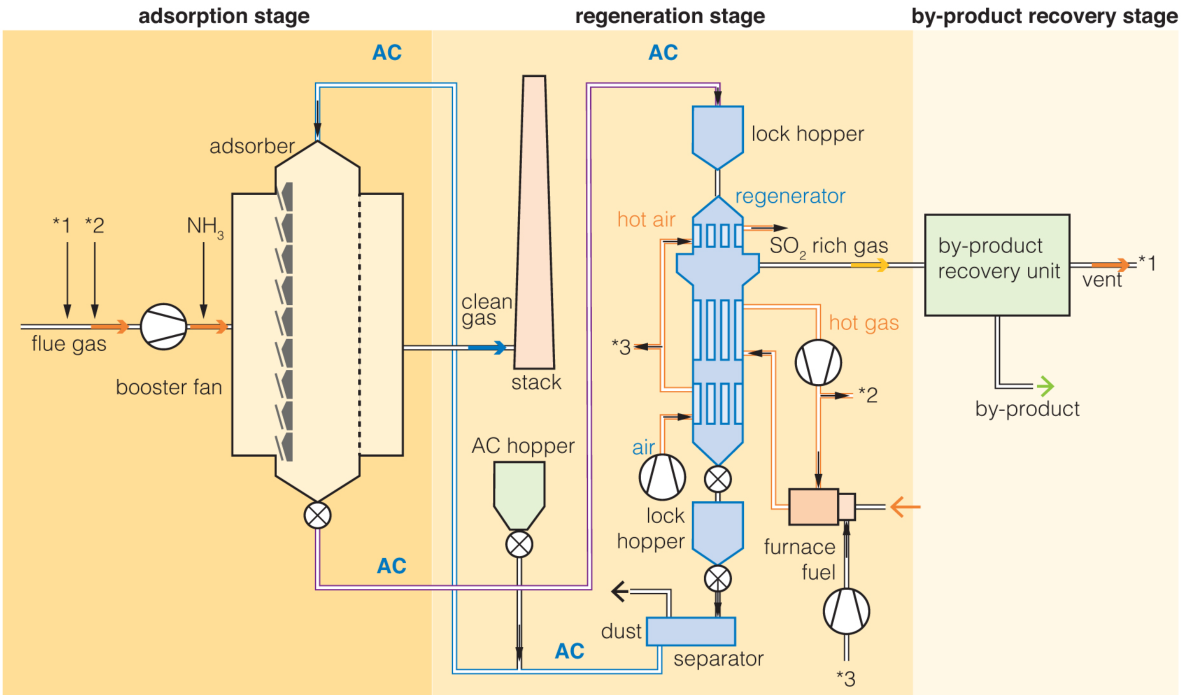

Figure 8 ReACT advanced multi-pollutant control technology (Peters, 2010)

Activated coke has been shown to be superior to activated carbon for mercury control for several reasons (Peters, 2010):

- higher specific surface area (more sites to capture mercury);
- smaller pore size;
- higher pore volume.

The coke in the ReACT bed is exposed to the flue gases for 80 hours. Regeneration temperatures are 450°C. At this temperature the mercury is desorbed but is held within the desorb zone. It then re-adsorbs at the top end of the regenerator and is therefore confined within a defined zone. Once the mercury in this zone reaches saturation capacity (usually 2–3 years) the coke is disposed of. The removed coke is then replaced. The ReACT system uses approximately 1 kt/y activated coke. This means that the ReACT system produces 25 t of solid waste every two years as compared with 45–47,000 t/y for ESP or baghouse based activated carbon systems. The mercury concentration of the waste coke is around 5400 ppm, significantly higher than the 40–140 ppm on activated carbon waste materials (Peters, 2010).

The system installed at Isogo (Figure 9) has been running for over five years and the React system has not become replete with mercury as yet, meaning that no mercury disposal has been required so far in the entire time that the system has been in operation.

Figure 9 React system at the Isogo Plant, Japan (photograph taken by the author during site visit, September 2014)

The advantages of the system are that it does not require any water, there is no plume visibility, the by-product is marketable and ash sales are not affected.

The 321 MW Weston coal-fired plant unit 3 in Wisconsin has just procured the ReACT system as part of its MACT compliance strategy, with the plant expected to be completed by 31 December 2016 (Williams, 2013).

3.3.4 Other projects at early commercial stage or still a demonstration phase

There are a number of multi-pollutant systems which have been mentioned and patented over the last decade or so but quite a few have either failed, stalled or simply not been sufficiently proven in the field to be taken to commercialisation. Table 3 shows a list of the technologies (discussed more above and below) which are emerging into the market with various levels of success.

Table 3 Multi-pollutant control process (after Carpenter, 2013)

Process	Description	Mercury removal	Status
Limestone scrubbers	Wet scrubbing with limestone slurry	75–99% oxidised	Commercial
Airborne Process	Dry/wet sodium carbonate injection and oxidant wash	99%	Commercial
NeuStream™	Ozone injection, dual-alkali scrubber	~80%	Commercial demonstration
SkyMine	Electrochemically produced NaOH scrubbing	90%	Commercial demonstration (on cement plant)
Spray dry scrubbers	Scrubbing with lime slurry, possible additional sorbent	0–95%	Commercial
CFBC scrubbers	Scrubbing with lime slurry, possible additional sorbent	>95%	Commercial
ReACT	Activated coke regenerable sorbent	>>90%	Commercial
Catalytic ceramic filters	Catalyst upstream of sorbent	>90%	Commercial
Max-9	Sorbent plus electrostatically enhanced filter	>90%	Commercial
TOXECON™	Pulse jet filter and sorbent	>90%	Commercial
E-Beam	Electron beam plus wet scrubber	>90%	Near commercial
ECO	Dielectric barrier discharge, wet scrubbing and solvents	>85% oxidised	Commercial
EPS	Oxidation and condensation	95%	Pilot/commercial
Lextran	Ozone injection and wet scrubbing	'some'	Commercial
LoTOx	Ozone injection and wet scrubbing	>90%	Commercial (petrol refineries)
CEFCO	Jet collision scrubbing	'some'	Pilot scale
Ashworth Gasifier-combustor (Clearstack)	Entrained flow air-blown gasifier with limestone	>93%	Near commercial

Dielectric barrier discharge (DBD) can be used to create ozone which acts as a useful oxidising agent. DBD is used in the ECO® system. Electro-catalytic oxidation (ECO) is applied downstream of an ESP – a barrier discharge reactor oxidises the flue gas and the more soluble products are then captured in a wet ESP (WESP) which also captures fine particles. The collected effluent from the WESP can be processed to produce concentrated sulphuric and nitric acids for sale. Mercury is captured in carbon filters at the liquid discharger. The system reduces SO_2 by 98%, NOx by 90% and mercury by 90% (demonstrated in a 1 MW slipstream at the First Energy R E Burger No5 unit, OH, USA). The technology is now marketed by Powerspan. However, there does not seem to have been any activity since the test at the Burger plant ended in 2010 (Powerspan, 2014). There was the suggestion of a commercial-scale project planned at Basin Electric's Antelope Station, but this has been cancelled (Carstens, 2014).

The Electron Beam flue gas treatment (EB-FGT) or E-Beam process irradiates the ammonia rich flue gas with high energy electrons and produces a nitrate fertiliser by-product. The system is reported to be up to 98% efficient for mercury removal. The process has been tested at pilot scale and also at full scale in several countries, including three demonstrations in China during the late 1990s and early 2000s and in Poland in 1999. However, it would seem that the relatively high investment and maintenance costs and the high auxiliary power consumption of the system has led to a lack of uptake in the marketplace so far (Carpenter, 2013).

The use of corona discharge for multi-pollutant control has also been tested by several companies since the 1980s. For example the ELFI technology developed in Serbia which passes the ammonia heavy flue gas through a plasma chemical reactor. ELFI has not reached pilot scale yet but a similar technology in China has been tested on a slip-stream of a 3 MW plant and in Korea on a 10 MW demonstration unit. However, these tests took place in the early 2000s and nothing appears to have advanced into the market since then (Carpenter, 2013).

The Eco Power Solutions (EPS) multi-pollutants air quality control system (MP-ACQ Reactor) is an ozone oxidation based multi-pollutant control system and was one of the shortlisted technologies for the MATS rule by the US EPA. Up to 95% mercury removal was achieved at pilot scale. The Lextran system, marketed from Israel, is another ozone based oxidation system combined with wet scrubbing. The system has been applied at full scale but on a steel plant in China (Carpenter, 2013)

In PEESP (plasma enhanced ESP) a reagent gas mixture passing through a corona discharge creates an electric field which, in turn, creates radicals, ozone and other reactive compounds in the flue gas which can help to oxidise mercury. A system has been patented and tested at bench scale (Travoulareas and Jozewicz, 2005) but nothing has been published to suggest it has reached commercialisation yet.

Although it is difficult to separate the aims of multi-pollutant control system designs, these ozone and plasma based systems appear to be designed primarily for the concomitant capture of SO_2 and NOx, with the capture of mercury in the wet scrubbing part of the process occurring as a co-benefit. And so the removal rate for mercury varies from being defined as 'some' to '>90%'.

Combining activated carbon with existing particulate control systems was discussed earlier. But new systems, with advanced particulate controls are emerging. For example, the Max-9™ system marketed by General Electric uses an electrically stimulated FF. The system is designed for particulate control but can capture 50–85% of the mercury and >90% mercury when activated carbon is used (Carpenter, 2013).

Enviroscrub (Palmann Process) is produced by Enviroscrub Technologies Corp and is based on regenerable sorbents through a baghouse or a spray dryer followed by FGD. There was a 0.5 MW test at the Ameren Hutsonville plant and a 1 MW test at Minnesota Power's Boswell Plant but nothing has been reported on the system recently (Carstens, 2014).

MerCAP (mercury control via adsorption) is based on the positioning of sorbent coated surfaces within the flue gas to capture mercury, with periodical regeneration and recovery of the captured mercury. Slip-stream field tests at full-scale plants have been carried out in the US but it would seem that the system had issues with degradation and has not yet been commercialised (NETL, 2014). E-beam, an electron beam process which aimed to remove SO_2, NOx and mercury simultaneously via irradiation with high energy electrons is another process which appears to have stalled.

Linde have a LoTOx system based on ozone injection upstream of a wet FGD system. The approach has worked well at commercial stage in the metal industry but does not yet seem to have reached commercial or even demonstration stage for coal-fired units (Travoulareas and Jozewicz, 2005).

Other multi-pollutant technologies that have appeared in recent literature include (Carstens, 2014; Carpenter, 2013):

- CEFCO, Global Clean Energy – modular reaction systems in series including 'metals reactor system' for mercury. 1–3 MW pilot project at Witchita Falls, TX. The system is also designed for CO_2 control;
- Comply 2000 – Eco Power Solutions – 5 MW pilot facility in Louisville, KY.

Clearstack Power LLC market an air blown gasifier system as a multi-pollutant control system. The pre-combustion unit is used to gasify the coal and limestone is included to capture the SO_2 and mercury. Tertiary air systems can also be added to help reduce NOx and CO emissions. The mercury is reported to be captured (>93%) in the slag as a CaHg amalgam. Over 80% of the ash is removed from the system before it enters the boiler resulting in a reduction of PM emissions. The slag and boiler ash can be sold for asphalt shingles or road bed material whilst the fly ash is generally of higher quality than before and suitable for cement. The system is reported to be suitable for lower grade and waste coals. There are ongoing feasibility studies at small and industrial boilers including a project at the Crawfordsville 12.6 MWe unit (Ashworth and Becker 2014). The Clearstack system avoids the need for downstream retrofitting and so may be of use to those plants with space or design constraints.

3.4 Relative cost

A direct comparison of the cost of the various technologies for mercury control is not possible as there are too many variables, such as:

- the ease of mercury removal (which varies with coal type and plant configuration, as discussed above);
- the layout and configuration of the plant (to determine the most appropriate system to suit each plant individually);
- the reduction required – it will be easier and cheaper to reduce mercury by 50% than by 90%, but legislation will determine what level is required;
- energy required for the control process (for systems using electrical and plasma technologies, which can be relatively high, up to 3–4% of total plant output, Carpenter, 2013);
- local variables – delivery costs, storage costs, potential effects on loss of fly ash sales.

It is possible to give an indication of relative costs of different approaches, along with caveats explaining the potential issues which would affect absolute cost. The CCC and the UNEP Coal Partnership produced a cost table for the Process Optimisation Guidance document (UNEP, 2010). Table 4 below gives an update on this information.

Table 4 Relative cost of Hg removal for various techniques

Approach	Capital cost	Incremental O&M cost	Comments
Increasing plant efficiency	moderate	low	Not a significant effect on mercury emissions but good for multi-pollutant emission plant output
Coal washing/treatment	High	moderate	Washing is less expensive than chemical treatment. Coal specific results
Coal blending	Very low	Very low	Will depend on coal availability. May require refurbishment of pulverisers
Coal additives	Very low	low	Can be sprayed on to coal or into boiler. Proprietary, so cost varies with supplier. May be issues with corrosive impacts on plant
Upgrading flue gas controls (ESP, FF, FGD)	variable	low	The cost of upgrading on modifying existing pollution control devices will vary on a case by case basis but could improve performance of the plant in more than just mercury control and is a one-off cost
Activated carbon injection	Low	low	Maintenance of new sorbent injection facility now required. High costs for waste management for some sorbents. However, newer sorbents are low cost and do not cost disposal issues
Multi-pollutant systems	New, therefore variable	variable	New systems are emerging into the market and need to be considered on a case by case basis

3.5 The decision making process

Before any decision can be made on investment in technologies can be made, there must be a full understanding of what is to be achieved. In most cases, this is not simply a requirement to reduce emissions of a single pollutant. For mercury, the decision must take into account:

- What is to be achieved at the plant in question? Is there a set emission limit? Is there a minimum reduction requirement?
- If I cannot achieve compliance, what are the alternatives? Retrofitting? Fuel switching? Closure?
- Is this reduction in emission in mercury only one of my considerations? Do I also have a reduction requirement for other pollutants? If so, how best can I reduce them all simultaneously?
- What are the limitations at my plant? Can I change fuel? Can I use existing control systems that I already have on site or will I need to invest in new technologies?
- Do I have the site space and the money available to make the required changes?

If the plant operator determines that emission reductions must be made, then the decision making process will move on to consider more specific requirements of each plant on a site-by-site basis. In order to make a decision on how best to control mercury at any specific plant, a great deal must be known about the plant-specific conditions. As mentioned previously, the key is having as much of the mercury present in the oxidised form as possible as oxidised mercury is relatively easy to capture in existing control systems. However, many different factors affect mercury oxidation including coal characteristics such as halogen and ash content. A knowledge of coal characteristics helps predict how best to control mercury from a coal.

There is one resource which has provided a significant amount of information which has arguably advanced the understanding of mercury in coal plants further than any other and that is the ICR – the Information Collection Request. In December 2009, the US EPA sent out the ICR requiring all power plants (coal and oil) to submit emission information for use in developing emission standards. The full details and results of the ICR can be found here: http://www.epa.gov/ttn/atw/utility/utilitypg.html

What the ICR provides is access to real data from the fleet of US coal plants in 2009 – data on coal type, coal characteristics and emissions. This is an incredible source of information for developing a better understanding of mercury behaviour in real plants and the data can be used to develop models to predict emissions under different plant conditions. The obvious drawback is, of course, that the ICR data relates only to US coals (or coals burned in the US) and US plants.

The ICR data has been used to develop several models for mercury behaviour based on coal characteristics and combustion conditions. However, Ticknor and others (2014) argue that these rely on a large number of measurements and a detailed understanding of combustion mechanisms. Instead Ticknor and others (2014) propose a technique based on artificial intelligence and have produced their own Bayesian regularised artificial neural network (BRANN) system based on five coal properties to predict mercury emissions under different conditions. Information for the system was obtained from the ICR, and fed into the BRANN system. The system considered 6 main parameters – the heating value of the coal, the Hg content, the chlorine content, the sulphur content, the ash content and the temperature. Figure 10 shows the relative contributions from each of these parameters to the determination of mercury speciation in the combustion system.

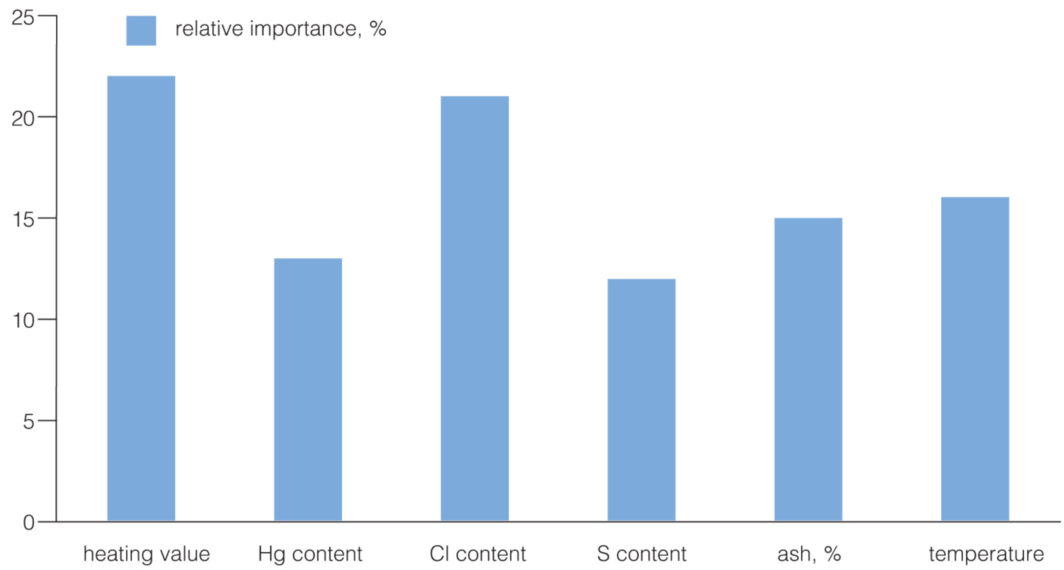

Figure 10 Contribution of input parameters to prediction of mercury characterisation, based on the BRANN model (Ticknor and others, 2014)

Ticknor and others (2014) emphasised that, although the model only used six parameters in this particular study, it could cope with significantly more which could enhance the model. The report concluded that, together with model parametric sensitivity studies, the BRANN model could act as a support tool for pollution control system design and operation. It is also likely that the tool could form part of a decision making process to determine the most appropriate mercury control approach on a site-by-site basis. As can be seen from the discussion in this chapter, there are many different options available for mercury control. The decision on which method to use must be made by an expert based on knowledge of the coal characteristics, the plant characteristics, the amount of control required, any control required on other pollutants which could be achieved simultaneously, cost and so on. It is not a simple decision to make and some plants will invest significant amounts of time and money in working through the options available to them, even running small-scale tests, in order to make the correct choice.

Obviously this decision would be easier if there were some form of decision tree to work through. During the development of the Minamata Convention, the UNEP Coal Partnership developed a POG – Process Optimisation Guidance document – which was intended to summarise the options for mercury control and help in the decision making process. The POG contained a decision tree, as shown in Figure 11.

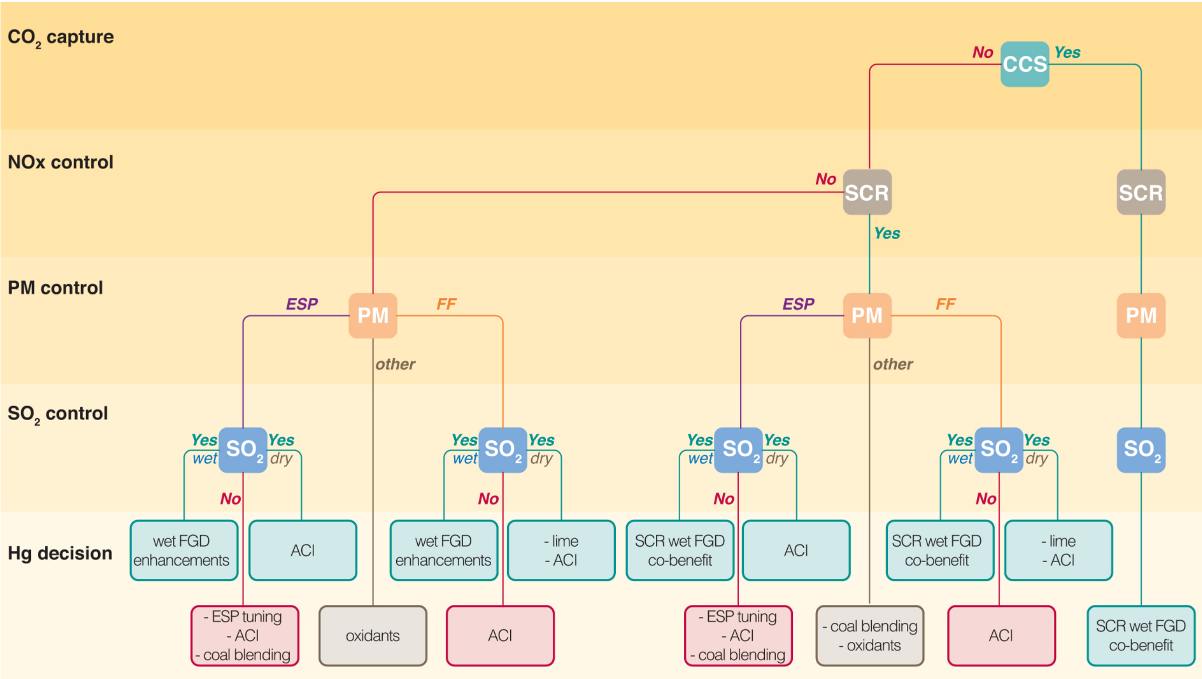

Figure 11 POG decision tree (UNEP, 2010)

The POG decision tree was relatively simplistic, referring the user to the relevant section of the main document for further reading. But it narrowed down the number of options which were relevant in each situation. The POG was met with enthusiasm and so EU funding was used to develop the iPOG, an interactive online/downloading programme which allowed any user to compare mercury control options. The iPOG can be downloaded for free from the link below:

http://www.unep.org/chemicalsandwaste/Mercury/PrioritiesforAction/Coalcombustion/ProcessOptimizationGuidanceDocument/tabid/4873/Default.aspx

The iPOG accepts information on coal type (such as ash content, sulphur content), plant characteristics (such as burner type) and any flue gas control systems in place (ESP, baghouse, FGD, SCR). The user receives an estimate of baseline mercury emissions from the plant. By returning to the programme and changing parameters such as the coal type, the addition of oxidants or sorbents, and flue gas control systems present, the user can get a feel for how much mercury reduction could be achieved with these modifications. Whilst the iPOG was never intended to replace expert consultancy, it has proved to be an extremely useful tool in terms of providing a quick and simple guide to different mercury control options for specific coals and plant types. One limitation of the iPOG is that the data used in the estimations of emissions are obtained from the US EPA's ICR (Information Collection Request) and the results are therefore based almost exclusively on data from coal plants in the USA. However, in order for the iPOG to be expanded to include data from outside the US, a significant amount of time and money would have to be invested.

Trovant (2013) has provided a simple guide to how to capture the different types of mercury in different control systems, as shown in Figure 12. For oxidised mercury, the options are straightforward as oxidised mercury can be captured by co-benefit effects. The same is true for particulate bound mercury, oxidised mercury which has already adsorbed to particles in the flue gas. Elemental mercury must be converted to either oxidised or particulate mercury to be captured. Trovant includes possible negative effects of some of the control options such as corrosion issues which would need to be identified and managed on a plant-by-plant basis.

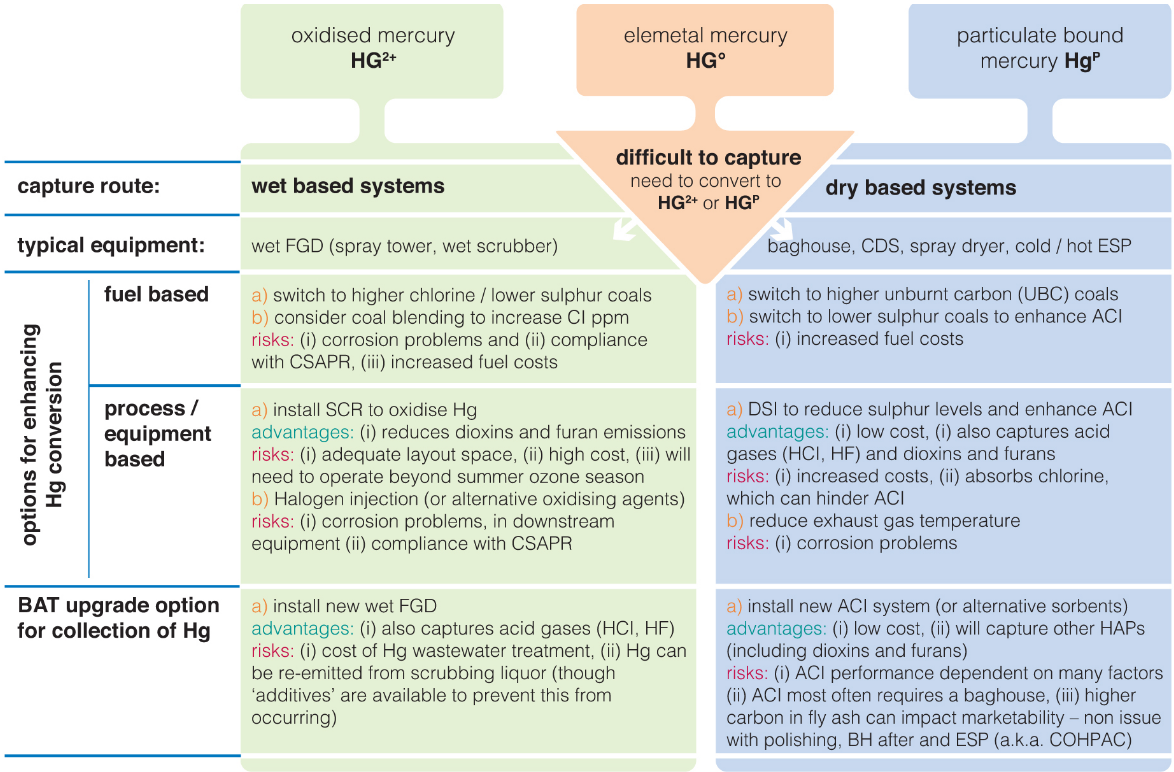

Figure 12 Summary of the challenges and opportunities for improving Hg collection from plant stacks (Trovant, 2013)

Trovant (2013) also produced a matrix table of control equipment options, as shown in Figure 13. The matrix is complex and so the interested reader is referred to the original article for full details.

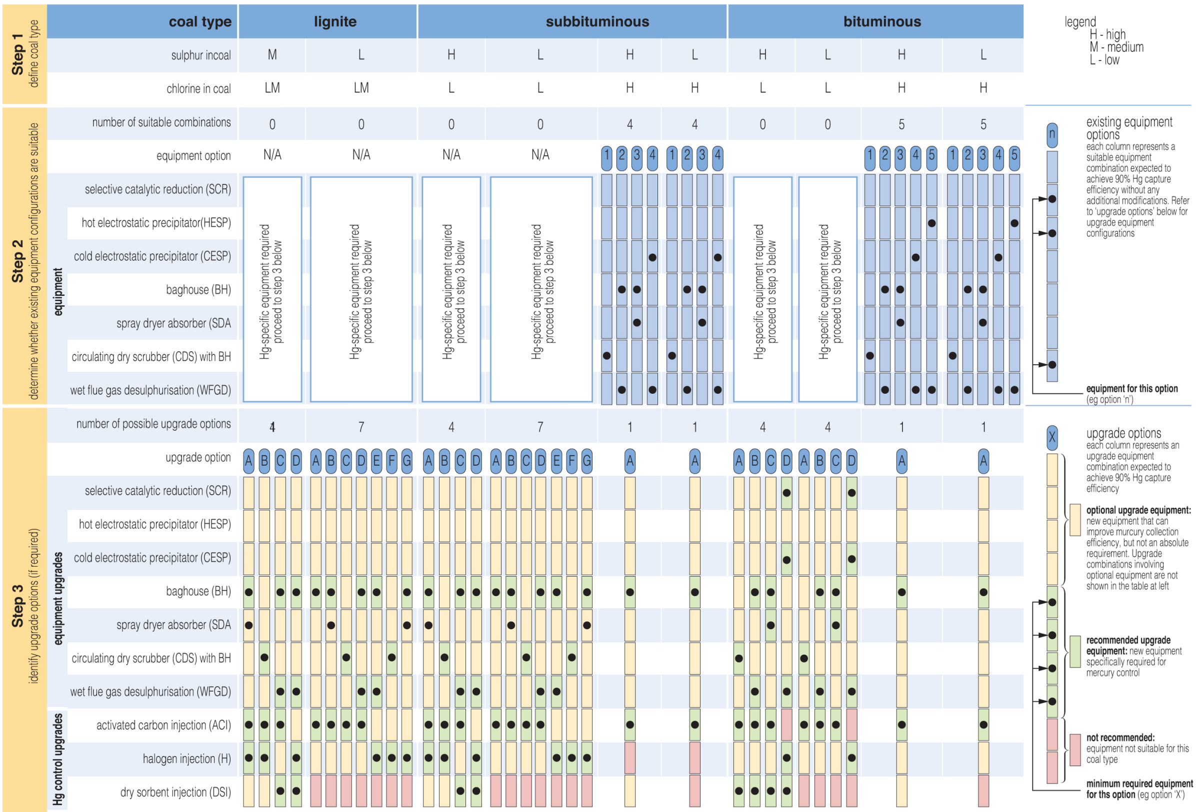

Figure 13 Matrix of mercury control equipment options

The matrix is aimed at finding an option to achieve 90% mercury collection for most coals other than lignite, where 80% is achievable. Obviously the matrix is, again, based on US plant data and on necessary assumptions on the performance of activated carbons and control systems which, in the real world, may vary significantly. The matrix, like the iPOG is meant to serve as a guide to potential options and not as a definitive decision making process. Decisions on mercury control must be made on a case-by-case basis, using plant-specific data and would normally include bench and short-term field trials on site to ensure that the system is working as predicted.

Coal type is listed first in the matrix as it is regarded as the most defining characteristic in terms of control options. Then the matrix considers which air pollution control devices are already in place to determine potential co-benefit effects. The next level identifies upgrade options which may be required to achieve MATS compliance. For example, a plant with high sulphur, high chlorine coal could already be in compliance if it already had one of the following installed: – a circulating dry scrubber with baghouse; a baghouse and wet FGD; baghouse and spray dry scrubber; SCR , cold-side ESP and a wet FGD; or SCR with hot-side ESP and wet FGD. If the plant does not have any of these combinations, then it could have to consider activated carbon injection with a baghouse (possibly an upgraded baghouse).

Although these programmes are available to help power plant operators to determine the most appropriate control technologies for their plant, the final decision will not be made without source specific testing at slip-stream, pilot or demonstration stage. The previous sections of this chapter have listed numerous commercial systems available and also mentioned where testing has or is taking place to test their suitability at different sites. Many plants will test more than one technology before making a final commitment.

3.6 Comments

There are many different means of reducing mercury emissions from coal combustion with the key being to have as much of the mercury in the oxidised form as possible, as this is the easiest form to capture. Plant managers can reduce mercury by making changes at almost any point in the coal combustion process chain – from cleaning, switching and blending the coal, through maximising capture in existing control systems to bolting on mercury specific control technologies. There are many commercial companies coming into the market selling various options for mercury control. For existing plants, the decision on the best system is not simple and must be made on a case by case basis. Flowcharts and computer programmes are available which can narrow down the choices for controls based on coal types and existing equipment. However, the final decision will not be made until testing has taken place on the plant itself. A quick look through this chapter and through recent power journals gives an indication of the large number of pilot and demonstration projects which are underway, especially in the USA, at the moment. The market is young and vibrant and the choice of systems is large and growing.

That said, however, it is clear there is a market being developed for mercury-specific control that offers a mercury reduction of >90% as is required at some plants. There are few, if any, plants that can consistently achieve this reduction rate with co-benefit effects. Average co-benefit effects offer up to around 70% mercury reduction in PM/FGD/SCR combination. That extra 20–30% can usually only be achieved by investing in a mercury-specific approach such as an oxidant or sorbent. Hence the emergence of the mercury specific control markets that are discussed in the Chapters to follow.

4 China

China is dependent on coal for 70% of its primary energy production – by the end of 2007, coal consumption was at 2727 Mt/y and around 1532 Mt of this was used in coal-fired power plants. Mercury emissions from coal-fired plants are estimated to have increased from 64.4 t in 1995 to 101 t in 2003, an annual growth rate of 5.9% (Tian and others, 2012).

The Ministry for Environmental Protection (MEP) in China has initiated guidelines for mercury from 40 different source types in China. With the size of the country and the number of small and unregulated sources, a coordinated approach is a significant challenge. According to Siying (2012) the country is unlikely to move to a real 'mercury-free' strategy within the next 20 years without financial support from the international community. However, as discussed in this chapter, there is certainly an indication that China is moving quickly towards cleaning up the power sector.

4.1 Legislation

There is an air quality crisis in the major cities in China and the cost with respect to public health and environmental damage through coal use is estimated at around 7% of GDP. China hopes to reach WHO (World Health Organisation) air quality standards in all cities by 2050 (Sloss, 2014).

The current emission limits for coal-fired boilers in China are shown in Table 5.

Table 5 Emission limits for coal-fired boilers in China from 2011*, mg/m^3 (Sloss, 2012)

Pollutant	Conditions	Limit, national	Limit in specified regions †
Soot	All units	30	30
	Plants in key regions§	20	
SO_2	New boiler	100	200
	Existing boiler	200	400
	Plants in key regions§	50	
NOx (as NO_2)	All units	100	400‡
	Plants in key regions§		
Hg and compounds	All units	0.03	0.03

* limit for mercury applies in 2015
† applies in Guangxi Zhuang Autonomous Region, Chongqing Municipality, Sichuan Province and Guizhou Province
‡ W-type thermal boilers, furnace chamber flame boilers, CFBC boilers and boilers in operation before 2004
§ key regions are those situated where development is concentrated, environmental capacity is low, vulnerable ecological environments and major air pollution problems

China has been steadily tightening air pollution emission standards in each of its Five-Year Plans. The current Five-Year Plan (12th Plan, 2011-15) continues to tighten requirements for reducing emissions from the power sector. All new coal-fired units must have FGD as standard and existing units which exceed set limits must also install FGD. Smaller, less efficient coal-fired units be closed down –this applies to small plants over 20 years old or with capacities below 200 MW. This will soon tighten to all plants under 300 MW.

These requirements resulted in co-benefit effects on mercury through both efficiency and capture routes. The China Council for International Cooperation on Environment and Development (CCICED, 2011) produced a study reviewing mercury in China. The study cited data which suggest that, had no legislation been applied, mercury emissions from the coal combustion for power generation sector would have increased, as shown in Figure 14. However, the different portions of the Five-Year Plan led to small but significant reductions in emissions.

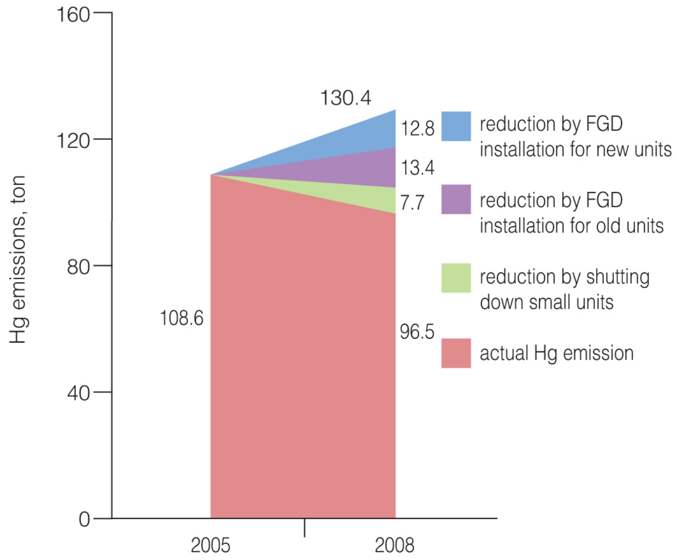

Figure 14 Illustration of the co-benefit of mercury removal by SO_2 control measures during 2005-08 (CCICED, 2011)

In addition to the legislation affecting SO_2, NOx and Hg directly, China has other legislation and action plans which may have additional effects on coal use and thus on emissions of all pollutants. Policies relating to climate change first appeared in China in 2007 in the 11th Five-Year Plan. In the 12th Five-Year Plan, coal policies were introduced, with the aim to control the increase in China's dependency on coal in the future. This was a non-binding target rather than a legal commitment. The current government is promoting 'sound and sustained economic development' supported by ecological modernisation and a 'coal cap'. The aim is to establish a non-binding cap on coal use by 2015 with an actual cap by 2020. This is a significant challenge considering the current rate of increase in coal use in China.

In September 2013 the 'air pollution prevention and control action plan' was created. Different reduction targets have been set for different areas and for different pollutants. The plan proposes that coal consumption peaks and start to decline by 2017 in key economic areas – Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta. It also bans the approval of new conventional coal-fired power plants in these key regions. Most importantly, the plan has already been accompanied by very ambitious targets for cutting coal consumption in the provinces of Shandong, Hebei and Beijing, as well as in the 16 million people megacity of Guangzhou. Motivated by the major role of coal in the overall air pollution problem in

China, the targets require an absolute coal consumption reduction of 40 Mt in Hebei, 20 Mt in Shandong, and 13 Mt in Beijing (Sloss, 2014a).

The current mercury emission limit for coal plants in China is a somewhat unchallenging 50 µg/m³. The report by CCICED (2011) suggests that a target of 15 µg/m³ could be met by 2015 and a tighter target of 3 µg/m³ by 2020. The emission limit could vary with plant size with small units (<75 MW) meeting the 10 µg/m³ limit after 2020 whilst larger units meet the tighter, 3 µg/m³ limit. If such an approach were adopted then emissions from the coal power sector could be reduced by a further 30% between 2007 and 2020.

Although there do not seem to be any mercury-specific controls in place yet in China, there are 16 demonstration projects for mercury online monitoring which have been running since 2012. The data from these systems will go a long way to help determine the behaviour of mercury in Chinese plants so that the most appropriate control options can be applied, should they become necessary in future.

4.2 Options for mercury control

All of the options for mercury reduction discussed in Chapter 3 could be applied in China.

4.2.1 Changes in fuel use

Chinese coals have mercury contents ranging from 0.02 to 1.92 mg/kg. However, the average mercury content of coals burned at Chinese coal plants is 0.19 mg/kg. Coals with the highest mercury contents (0.25–0.45 mg/mg) are consumed in the southwest region, including the provinces of Chongqing, Guizhou and Yannan. Tian and others (2012) note that selective mining for lower mercury coals has already been raised as an option for reducing mercury emissions in Guizhou and Guangxi provinces, which have some coals with particularly high mercury contents. However, since plants in this region are designed to burn local coals, the change would not be simple. Further, the national strategies from the Chinese government are currently aiming to promote economic development in these provinces, and to increase the supply of electricity from west to east and to solve the electricity supply shortage in the southern regions. And so, with mining so closely linked with the local economy and regional development strategies, major changes such as mine closures to avoid higher mercury coals are unlikely to be considered in the foreseeable future.

An emission factor study has been carried out by Wang and others (2014) to compare mercury emissions from coal-fired plants in Northern China (Beijing, Hebei, Inner Mongolia, Shangxi and Tianjin) in 1995, 2003, 2011 and projected for 2015. The study considered the mercury contents of the coals used in the different regions and the relative amounts of coal washing applied, if any. The study noted that the mercury contents of coals in most regions did not change. However, there was a significant change in the mercury contents of coals burned in Beijing in 2003, up from 0.195 mg/kg in 1995 to almost 0.22 mg/kg in 2003 – this was reported to be due to the increased use of native coals which are relatively high in Hg. The Hg content then dropped to 0.175 mg/kg in 2011 as more imported coals were used, with lower Hg contents. This reduction of coal mercury contents from almost 0.22 mg/kg in 2003 to below 0.18 mg/kg in 2011 could have had a significant effect on total Hg emissions in the region since, according to the study, only 24% of plants had FGD installed in 2003.

Coal washing could be especially useful in China as it has been reported that Chinese coals demonstrate average mercury removals of over 50% with almost all physical coal washing processes. Currently only 20% of total raw coal in the country is washed and most of the washed coal is used in coke making in the iron and steel industry. Although coal washing clearly could be an effective method of reducing mercury emissions, coal companies are not keen to introduce the practice due to the additional cost of capital investment in cleaning equipment. There would also be the issue of potential water contamination and new solid waste streams created at coal washeries (Tian and others, 2012).

Around 85% of the coal used in the power sector in China is bituminous, 10% is anthracite and 5% lignite. Since Hg from bituminous coals tends to be in the oxidised and easier to capture form, this is good news for China in terms of the potential for co-benefit mercury reduction.

4.2.2 Co-benefit reductions

As shown in Section 4.1, China's legislation is heavily focussed on flue gas cleaning with FGD and, soon, SCR technologies. This will have a significant effect on mercury emissions through co-benefit effects. At the moment, the current limit for mercury does not require mercury-specific technologies. Tian and others (2012) comment that '*the combination of conventional PM and SO_2 control systems can attain well co-benefit Hg reduction effects, which is a cost-effective choice for Hg removal in coal-fired plants in China*'.

However, it is possible that the next Five-Year Plan could set a lower limit for mercury in some regions. Should this happen, plants will have to consider the most appropriate methods for mercury control on a plant-by-plant basis. Those plants which produce mercury in the harder to capture elemental form may find that co-benefit effects are not enough to reduce mercury emissions. Tian and others (2012) suggest that demonstration projects on advanced technologies should be initiated and accelerated in order to achieve mercury reduction in China in the future.

The extent to which mercury will be controlled in China will depend on the tightening and strict application of emission reduction strategies. Wang and others (2010) estimated the potential changes in mercury emissions between 2010 and 2020 based on several different strategies. Following the trajectory based on the increase in mercury emissions between 2005 and 2010, emissions under a 'business as usual' strategy could mean mercury emissions from the coal sector increasing from 155 t/y in 2010 to over 190 t/y by 2020. However, the application of an extremely 'strict' control strategy could see mercury emissions reduced significantly, even to as low as 80 t/y. However, Wang and others (2010) suggest that the most probable scenario is that mercury emissions will continue to increase for the next few years but then decline, reaching 130 t/y by 2010.

Zhao and others (2013) studied the effect of the 12th Five-Year Plan on mercury emissions as a result of the installation of different control technologies to control particulates, SO_2 and NOx. The installation rates of control technologies are expected to change between 2010 and 2015 as follows:

	2010	2015
ESP alone	14%	0%
ESP + WFGD (wet FGD)	66%	15%
FF + WFGD	6%	2%
SCR + ESP + WFGD	14%	75%
SCR + FF + WFGD	0%	8%

This is over and above the control technologies which are already in place in China. There is clearly a move from most plants having ESP and FGD to most plants having ESP and FGD plus SCR installed. There will be no plants which do not have FGD installed after 2015. What this means is significant potential for mercury control through co-benefit effects. Zhao and others (2013) estimated the mercury distribution through these various plant configurations in 2010 and 2015, as shown in Tables 6 and 7.

Table 6 Mercury coal-fired power station output distribution factor in 2010, % (Zhao and others, 2013)

		Atmoshphere			Water	Solid		
Combustion process	Flue gas treatment	System air leakage	Stack	Total		Boiler residue	Dust/ particles	Total
Turbulent burner	ESP	5	71	76	0	0	24	24
	ESP+WFGD	5	16.5	21.5	54.5	0	24	24
	FF+WFGD	5	23.4	28.4	43.1	0	28.5	28.5
	SCR+ESP+WFGD	5	13.5	18.5	57.5	0	24	24
	SCR+FF+WFGD	5	2.1	7.1	64.0	0	28.5	28.5
Direct flow burner	ESP	5	70.9	75.9	0	0.1	24	24.1
	ESP+WFGD	5	16.5	21.5	54.4	0.1	24	24.1
	FF+WFGD	5	23.4	28.4	43	0.1	28.5	28.6
	SCR+ESP+WFGD	5	13.5	18.5	57.4	0.1	24	24.1
	SCR+FF+WFGD	5	2.1	7.1	64.3	0.1	28.5	28.6

Table 7 Mercury coal-fired power station output distribution factor in 2015, % (Zhao and others, 2013)

		Atmoshphere			Water	Solid		
Combustion process	Flue gas treatment	System air leakage	Stack	Total		Boiler residue	Dust/ particles	Total
Turbulent burner	ESP	5	52.2	57.2	0	18.8	24	42.8
	ESP+WFGD	5	11.3	16.3	40.9	18.8	24	42.8
	FF+WFGD	5	15.6	20.6	32.1	18.8	28.5	47.3
	SCR+ESP+WFGD	5	9.3	14.3	42.9	18.8	24	42.8
	SCR+FF+WFGD	5	1.4	6.4	46.3	18.8	28.5	47.3
Direct flow burner	ESP	5	70.6	75.6	0	37.5	24	61.5
	ESP+WFGD	5	11	16	22.6	37.5	24	61.5
	FF+WFGD	5	5.2	10.2	23.9	37.5	28.5	66
	SCR+ESP+WFGD	5	6	11	27.6	37.5	24	61.5
	SCR+FF+WFGD	5	0.9	5.9	28.2	37.5	28.5	66

Between 2010 and 2015 we see a significant move from the majority of emissions leaving the plant via the stack and the water to being captured in the boiler residue and particulate control devices. Zhao and others (2013) emphasise that, although this means lower emissions to the atmosphere, there may be increased concern over the concentrations of mercury in solid and liquid wastes.

Ye and Wang (2013) studied two policy scenarios to compare the effects of policy on the energy sector in China. Modelling was performed based on data from 2006 to 2010 on energy demand, electricity generation and installed capacity. Coal characteristics were obtained from previously published literature. The Scenario A (baseline) assumed not so much a business as usual approach, but more a 'do nothing' approach, whereas Scenario B assumed emission reduction targets for SO_2 and NOx based on the 12th Five-Year Plan (13.6% reduction in SO_2 and 21.1% for NOx in both 2015 and 2020, based on 2010 levels). The model assumed a growth in the energy sector from 962 GW in 2010 to 1487 GW in 2020. The model predicted a significant increase in FGD, low NOx burners and SCR installations under Scenario B, unsurprisingly. But the model did appear to highlight that the emission targets would result in an increase in the retrofitting of control technologies onto existing plants and not a significant move to alternative fuels.

The model predicted that mercury emissions would increase by 158% under Scenario A (from a starting value of 88.5 t in 2010). However under Scenario B, emissions would actually decrease by 46%. Although China has now moved on significantly from the aims of the 12th Five-Year Plan, this study demonstrated that, even under previous policies which concentrated only on SO_2 and NOx and not on Hg, Hg emissions could be reduced significantly due to co-benefit effects. However, CO_2 emissions could increase during the same period by 0.64% as a result of the electricity demands of the additional pollution control equipment being installed under Scenario B (Ye and Wang, 2013).

Figures 15 and 16 show the rate of installation of control devices in the different regions of Northern China. The installation rate of FGD has been unprecedented and complete. The rate of SCR is somewhat slower, but is likely to continue until all plants are retrofitted as standard. Unsurprisingly, emissions of mercury are affected by this retrofitting.

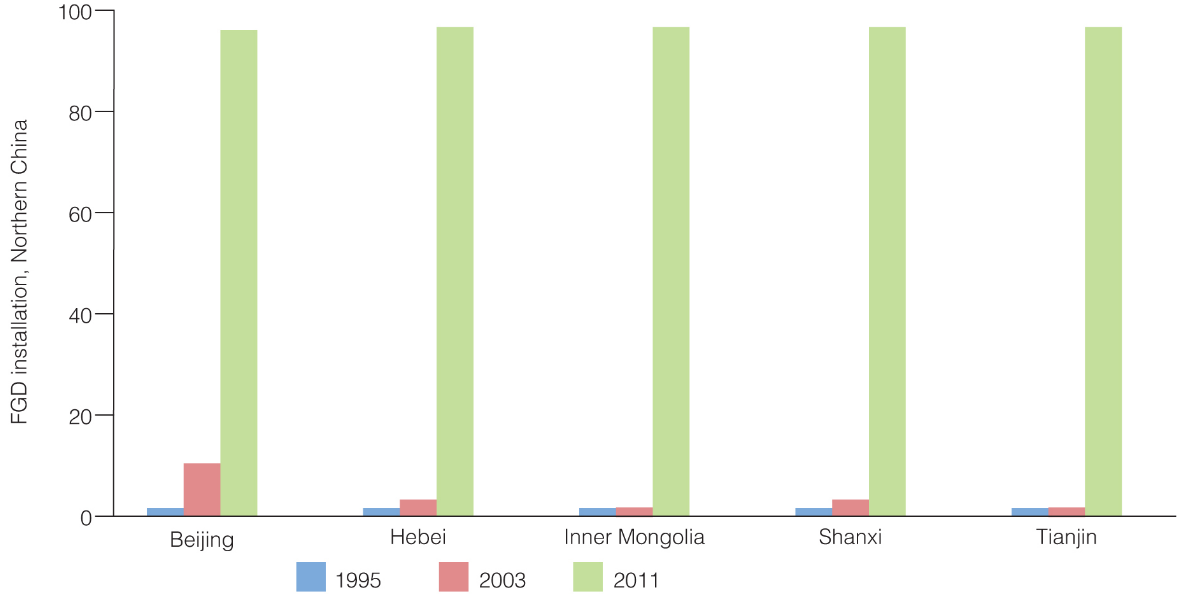

Figure 15 Installation rate of FGD in regions of Northern China between 1995 and 2011 (Wang and others, 2014)

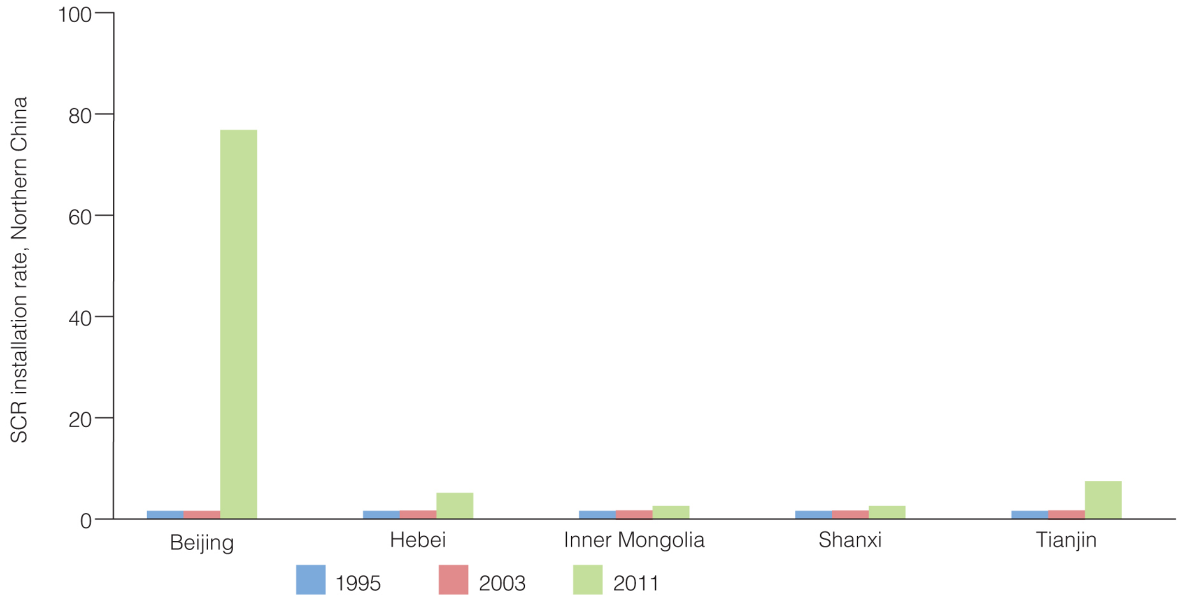

Figure 16 Installation rate of SCR in regions of Northern China between 1995 and 2011 (Wang and others, 2014)

Figure 17 shows mercury emissions from the different regions through the period of the installation of the control technologies. As can be seen, mercury emissions from Beijing and Hebei appear to be coming under control but those from the remaining regions are still increasing. This may be due to the fact that the FGD and, to a greater extent, the SCR technologies have only been installed very recently and so the effects of co-benefit reduction are still to be realised. Unsurprisingly, although the data are not available to show this, the mercury emissions correlate with increased coal use in those regions, outside Beijing, which have not had FGD installed within the period studied. Wang and others (2014) projected the mercury emissions for 2011 to 2015 and showed that, although coal consumption in Northern China would increase from around 360 Mt to 430 Mt during this period, mercury emissions would only increase from 21 t to 22 t, showing a slight decoupling of mercury emissions from the rate of coal use. For the whole study period, from 1995 to 2015, the mercury emissions from coal plants were expected to increase by 77.8% whilst coal consumption increased by 325.5%. As the installation rate of FGD and, later, SCR increase, the mercury emissions should not only stop increasing but should decouple completely from coal use and start to show an actual decline in real terms.

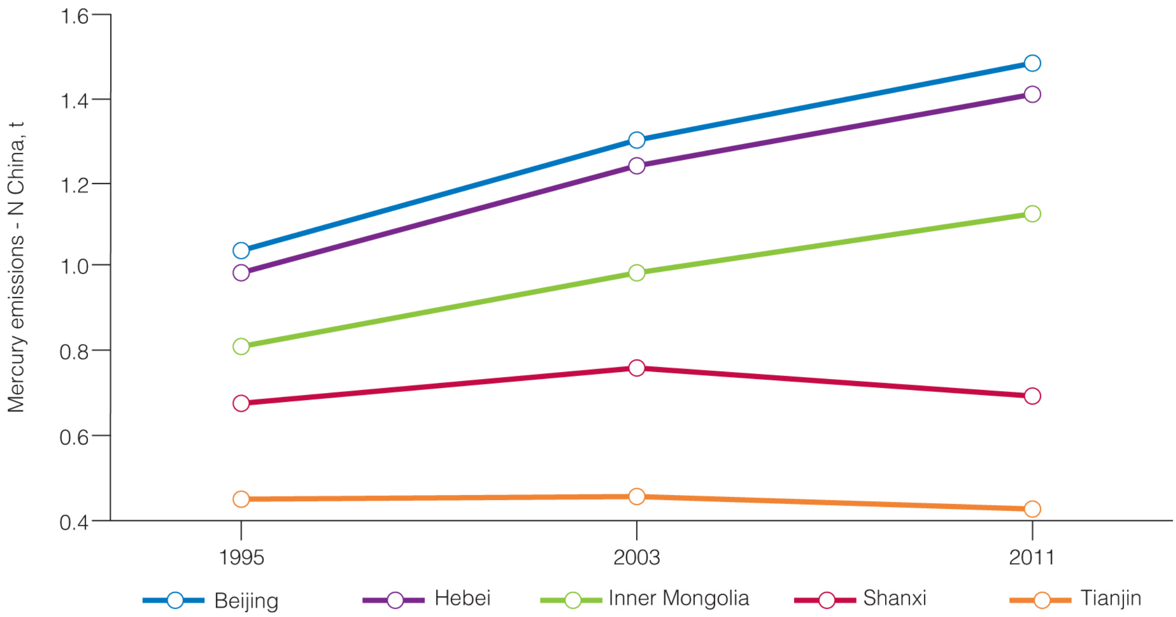

Figure 17 Mercury emissions from different regions in Northern China, 1993-2011 (Wang and others, 2014)

Reductions in mercury emissions in China in the forthcoming years are largely a result of the installation of FGD. However, as the country moves towards tackling NOx emissions by installing SCR on some plants, this will also result in an enhanced co-benefit mercury reduction. Tian and others (2012) estimate that an additional 10–20% reduction in mercury emissions could be achieved if SCR are widely applied across the coal sector in China.

4.2.3 Sorbents

According to Tian and others (2012), the Chinese power industry has little experience in the design or operation of activated carbon-based systems to date, largely as it is not required by the legislation. It is therefore likely that application of sorbents in China could encounter some challenges. Further study of sorbent applicability on Chinese coals and in Chinese plant configurations would be required along with several full-scale demonstration projects before the technology could be rolled out in large numbers. Further research could also improve understanding of sorbents in such a way as to increase the ease of use and reduce costs in the Chinese market. Thought would need to be given to sources and transport of sorbents, including domestic manufacturing facilities. Changes to the use or disposal of sorbent containing wastes and ashes would also need to be considered (Tian and others, 2012).

4.2.4 Multi-pollutant systems

According to Trovant (2013), unlike the retrofitting of co-benefit equipment which is under way on a massive scale in the USA, China is moving faster into the design and incorporation of mercury control into green-field projects from the ground up. This means that many Chinese plants will fit multi-pollutant control options to capture many pollutants simultaneously rather than bolting on particulate, SO_2, NOx and mercury systems separately. Trovant (2013) suggests that this experience will quickly move the Chinese vendors to the forefront of mercury control technology development. One of these vendors is China Huaneng Clean Energy Research Institute Ltd (CERI), a division of the state-owned China Huaneng Group, which has a total installed capacity of about 115 GW. Mercury removal upgrades have been installed at the Huaneng Beijing Cogeneration Power Plant (HBCP). CERI is also working on 'coordinated optimisation' of flue gas cleaning systems with optimised monitoring and control. Other approaches being considered by CERI are the use of low-mercury coals and addition to calcium bromide into the fuel coal or into the burners and the addition of reagent to wet FGD solutions.

As mentioned in Chapter 3, the Airborne Process™, a multi-pollutant control system based on a combination of scrubbers, oxidants and sorbents, is currently being tested at two commercial sites in China (Carpenter, 2013). No further information could be found on these projects. It is also known that the BRICC (Beijing Research Institute for Coal Chemistry) has been working on a regenerable coke sorbent system similar to the ReACT system discussed in Chapter 3, but nothing seems to have been published on this work.

The E-Beam process, an ELFI-type process and the Lextran ozone oxidation system have all been tested in China over the last two decades (*see* Section 3.3.4) but nothing has been published to suggest that these systems have made any headway into the Chinese market.

4.3 Comments

China has made incredible changes recently in air pollution regulation and is installing control technologies such as FGD and SCR at an unprecedented rate. The resulting co-benefit effects on mercury reduction are already becoming evident in some regions. The current mercury emission limit in China is not challenging, but this may change. Continuous emissions monitoring data are being collected from 16 full-scale plants which will help understanding of the behaviour of mercury in Chinese combustion systems. Although there is not much published on mercury specific control technologies in China, the size of the potential market would suggest that it is certainly on the commercial sector's radar. Work is being carried out at laboratory and pilot scale to determine the most appropriate and cost-effective technologies for Chinese plants but little is being published on this work. In addition to the vast market for enhancing mercury co-benefit reduction at existing plants with FGD and SCR, China could have the largest global market for multi-pollutant controls – the continued growth in the coal sector in some regions will allow operators to at least consider options for multi-pollutant systems rather than simply bolting on the standard FGD and SCR systems which are standard for older units. Multi-pollutant control can be built into the design of newer plants so that the plant will comply with both current and potential future legislation on emissions of a variety of pollutants.

5 Europe

This Chapter summarises the legislation set at the EU level which is relevant to emissions from coal combustion. Individual EU Member States may set their own additional national legislation as long as it is in line with, or more stringent than, that set by the EU. The Chapter also focuses on how much mercury reduction is being achieved with current legislation and discusses what might happen should the European Commission decide that further control is necessary.

5.1 Legislation

The EU launched a mercury strategy in 2005 which included 20 different approaches to reduce mercury emissions, cut supply and demand and to protect against exposure. However, none of these related directly to emissions from the coal sector. Emissions of mercury in the EU decreased by 67% between 1990 and 2009 to a total of 73 t (CCICED, 2011).

The EU has tightened emission limits on particulates, SO_2 and NOx via the Large Combustion Plant Directive (LCPD) and the Integrated Pollution Prevention and Control Directive (IPPC), as well as having to comply with ceilings for emissions of these pollutants under the Gothenburg Protocol. Whilst the LCPD set strict emission limits for PM, SO_2 and NOx, based on plant size, the IPPC was more permit-based, working on best environmental practice (BEP) and best available technology (BAT) principles. Operators found these two directives overlapping but not always complementary and often the limits specified under one directive disagreed with those specified under the other. To clarify the issue and ease confusion, the EU combined the LCPD and IPPC, along with 5 other directives which related to emissions from stationary sources, into one new directive – the Industrial Emissions Directive (IED). The IED, which will come into force in 2016, sets out strict emission limits for PM, SO_2 and NOx.

Table 8 Emission limits for SO_2 for plants under the IED, mg/m^3 (Sloss, 2012)

Plant size, MWth	Coal, lignite and other solid fuels	Biomass	Peat	Liquid
50–100 (pre-2013 plants*)	400	200	300	350
50–100 (post-2013 plants*)	400	200	300	350
100–300 (pre-2013 plants)	250	200	300	250
100–300 (post-2013 plants)	200	200	300	200
>300 (pre-2013 plants)	200	200	200	200
>300 (post-2013 plants)	150	150	150	150

* Plants are split depending on whether they were permitted prior to 2013 or after

Table 8 shows the emission limits for SO_2 for plants permitted before and after 2013 firing different fuel types. The limits are stricter for larger plants and are also stricter for newer plants. Smaller plants (<300 MWth) firing liquid fuels and peat are allowed slightly higher emissions than plants firing coal. For plants which cannot meet these limits due to specific fuel characteristics, the reduction requirements are different, as shown in Table 9

Table 9 Desulphurisation rate required for SO_2 for plants with challenging fuel (Sloss, 2012)

Plant size, MWth	Pre-2002 plants	Pre-2013 plants	Post-2013 plants
50–100	80	92	93
100–300	90	92	93
>300	90	93	96

Again the reduction is much more challenging for newer plants and for larger plants.

In most instances, regardless of plant size and age, meeting the requirements without the use of FGD will be a challenge. A few plants will use low sulphur coals and, for these plants, there is a potential derogation period of 6 months which will be permitted during instances of interruption in the supply of low-sulphur fuel.

The emission limits for NOx also vary with plant size and age. As shown in Table 10, the limits are tighter for larger and newer plants. Again, although some plants may be able to reduce NOx emissions to meet these limits using different coals and/or low-NOx burners, a significant number will be required to install SCR systems to achieve compliance.

Table 10 Emission limits for NOx for plants under the IED, mg/m^3 (Sloss, 2012)

Plant size, MWth	Coal, lignite and other solid fuels	Lignite	Biomass and peat	Liquid
50–100 (pre-2013 plants*)	300	450	300	450
50–100 (post-2013 plants*)	300	400	250	300
100–300 (pre-2013 plants)	200	200	250	200
100–300 (post-2013 plants)	200	200	200	150
>300 (pre-2013 plants)	200	200	200	150
>300 (post-2013 plants)	150	200	150	100

* Plants are split depending on whether they were permitted prior to 2013 or after

The IED does not include an emission limit for mercury. However, annual mercury monitoring is now required which implies that the European Commission is gathering information on emissions of mercury from different sources and this may mean that action will be taken in future. Further, the new BREFS (BAT reference documents) which list options for pollution control systems under legislation in the EU, include options for mercury control.

The combination of the requirements of the old IPPC and LCPD Directives, the Gothenburg Protocol ceilings and the new IED all come down to the fact that any plant which wishes to continue operation into the next decade must be fitted with state of the art PM controls, FGD (or equivalent) for SO_2, and either low NOx burners and/or SCR for NOx control. This means a significant co-benefit mercury reduction on all plants. Discussions on future legislation for the EU is focusing on further reductions of these pollutants beyond 2025.

Although the IED does not prescribe an emission limit for mercury from stationary sources, it does include BAT-associated emission levels – that is, it defines the mercury emission levels which should be achieved if BAT options (*see* Section 5.2) are applied. At the moment, the draft BREF document lists a BAT-AEL – BAT achievable emission levels as shown in Table 11.

Table 11 BAT associated emission levels for mercury from the combustion of coal (EC, 2013)

Plant size. MWth	BAT-AEL, µg/m³ New plants	BAT-AEL, µg/m³ Existing plants	Averaging period	Monitoring frequency
Anthracite and bituminous coals				
<300	0.5–5	1–10	Average of samples over 1 year	4 times per year
>300	0.2–2	0.2–6	Yearly average	Continuous measurement
Subbituminous coals and lignite				
<300	1–10	2–20	Average of samples over 1 year	4 times per year
>300	0.5–5	0.5–10	Yearly average	Continuous measurement

Individual countries in the EU may set their own, more stringent emission legislation. As yet, no country has set national emission limits for mercury which require action in terms of mercury control. However, it would seem that there are at least two plants in Germany and the Netherlands which have plant-specific mercury emission limits of around 2–4 µg/m³ (Sloss, 2012). This limit is challenging and would require some form of mercury specific strategy or at a multi-pollutant system which included mercury control.

5.2 Options for control

As mentioned above, previous and current EU policy has achieved some significant mercury reductions in the last few decades and so, to some extent, the EU does not have the same pressure to reduce emissions as there is in some other countries. That is not to say that nothing is being done. Rather that the EU has time to take stock of the reductions achieved so far, estimate what further reductions may occur as a result of current and impending legislation and policies and to focus on the most cost-effective strategies which may be required if, in the future, further reductions are deemed necessary.

The EC has not yet completed the BREFs which will outline the BAT for mercury control at large-scale coal-fired power plants. However, the current draft (EC, 2013), lists the proposed options. These are listed in Table 12. This is still a draft and therefore subject to change, but at this stage the options for mercury control are very much in line with the options discussed in Chapter 3 – everything from fuel cleaning and switching, through co-benefit effects to sorbents and oxidants. Without there being a strict emission limit to reach, it is difficult to predict what level of reduction in emissions will be required which, in turn, means that it is not currently possible to estimate how a mercury control market may develop in the EU.

Table 12 BAT for mercury (EC, 2013)	
Technique	**Applicability**
Bag filter (FF)	Generally applicable
ESP	Generally applicable (better removal efficiency at <130°C)
SCR	Generally applicable
FGD (wet or dry)	Generally applicable where these is a need to reduce SO_2 emissions
Fuel choice	Selection of coal/lignite at <25 µg/kg mercury, applicable within the constraints associated with the availability of different types of fuel, which may be impacted by the energy policy of the Member State
Sorbent	Generally applicable
Oxidants	Applicable in the case of low halogen content in fuel, with the constraints associated with the control of halogen emissions to air
Fuel pre-treatment (washing/blending)	Applicability is subject to a previous survey for characterising the fuel and for estimating the potential effectiveness of the technique

5.2.1 Changes in fuel use

As listed in Table 12, the EU has recognised that coal washing and blending is an option for mercury control and has also recognised that the applicability of this will need to be determined on a case-by-case basis.

There are significant changes happening in the share of energy production from different sources in the EU. The EU has a clear vision of moving towards a lower carbon future, with goals for renewable use and CO_2 reduction pushing carbon-based fuels such as coal out of the energy mix.

Rafaj and others (2014) have looked at the potential change in the energy mix in the EU-27 (as of 2010), and non-EU regions (countries in the EU region, and 'some neighbouring countries in the Middle East and North Africa regions'. The study compared future energy use under and baseline (business as usual) scenario and under a Maximum Renewable Power scenario, which assumes decarbonisation of the EU energy system and the highest possible electricity generation from renewables by 2050. The results are shown in Figure 18.

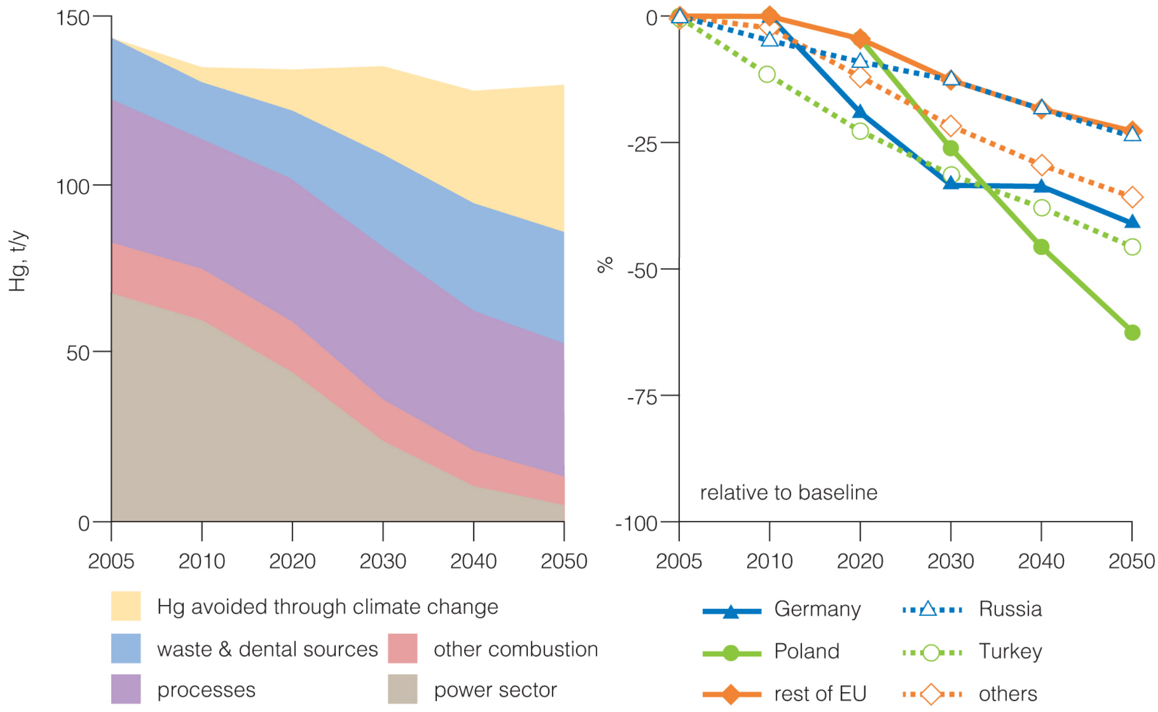

Figure 18 Maximum renewable power scenario: mercury emissions in Europe by sector (left) and reductions for selected regions (right) (Rafaj and others, 2014)

The left figure shows how almost 150 t/y of mercury may be avoided between 2005 and 2050 assuming the Maximum Renewable Power scenario. The greatest reduction (64%) could be achieved by replacing coal with renewables for power generation. Whilst this is an admirable goal achieving it in practice would be a significant challenge. The right hand figure shows what this would mean for the major countries within the EU. The greatest reduction could be achieved theoretically in Poland because of Poland's dependence on coal for the majority of its energy demand. However, Poland would find it a significant challenge to move entirely to renewables by 2050 as the complete closure of a major power sector in this time period is unlikely.

Figure 19 shows the potential change in mercury emissions from the power sector in the different regions, under the different scenarios, for 2005, 2030 and 2050. For the EU-27, even the baseline scenario suggests a significant move away from coal within the next 20–30 years. Although the maximum renewable scenario would take a while to move into reality, the difference it would make to the energy mix would be huge and mercury emissions would be minimised. For the non-EU region, population growth and increased energy demand mean that coal use will increase in the forthcoming decades and, without action, this will clearly increase mercury emissions. Under a maximum renewables option, this effect would be negated. However, again it is important to remember that the maximum renewables scenario is somewhat unlikely to be realised at this scale within this timeframe in these regions without some significant change in policy and investment in the funding for renewable power.

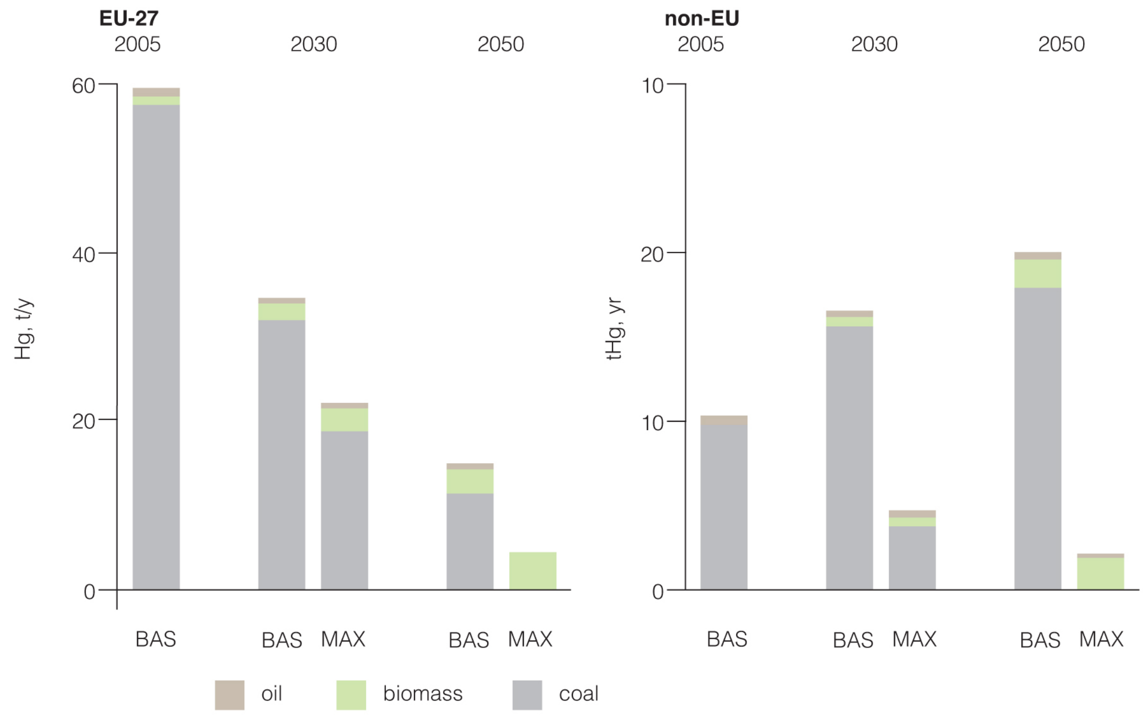

Figure 19 Mercury emissions from the power sector by fuel in the EU-27 and non-EU countries (Rafaj and others, 2014)

In addition to emphasising the potential importance of renewables, Rafaj and others (2014) also emphasise the importance of policy in the EU for reducing mercury emissions. Current mercury emissions in the EU total 145 t/y and it is likely that this total could remain relatively stable in future, with coal and lignite being responsible for 60% of the total. This study estimated that 'current standards to control air quality (dust sulphur and nitrogen oxide emissions) reduces the emissions of mercury by about 35%'. This estimate seems surprisingly low, considering the current and impending installation rate of PM controls, FGD and SCR throughout the EU under the IED. Those countries in the EU-27 should expect to see their mercury emissions peaking and, hopefully, dropping in the future. However, non-EU countries, where growth rates in fuel use are highest, could counteract the reduction in mercury elsewhere. The potential for renewables to contribute to reducing mercury emissions would be highest in these growth regions, as emphasised in Figure 19.

5.2.2 Co-benefit reductions

As discussed above, although the EU does not yet target mercury emissions from coal combustion specifically with emission limits, co-benefit effects from the IED and the concomitant requirement for FGD on almost all plants and SCR on many plants should be significant. There does not seem to be any data published that shows this effect for the coal sector alone. However, Figure 20 shows the overall reduction in total mercury emissions from EU countries between 1990 and 2011.

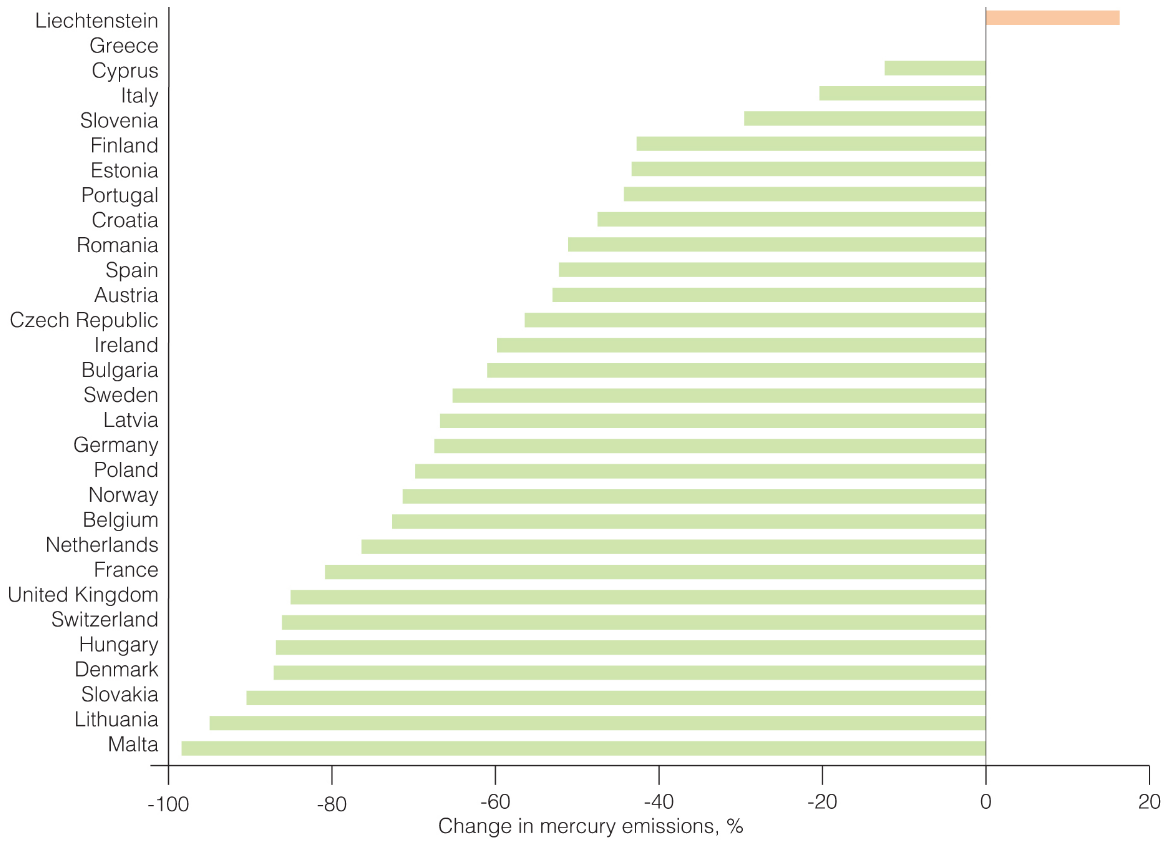

Figure 20 Reductions in mercury emissions in EU countries between 1990 and 2011 (EEA, 2014)

Apart from a few countries where the emissions are likely to be low already, the majority of the EU has achieved significant reductions in mercury emissions over the last two decades. This is why the EU has not had the sense of urgency on mercury emissions from the coal combustion sector that has been seen in North America. The co-benefit effects of the existing legislation are already evident.

5.2.3 Mercury specific controls

At the moment, sorbent use for emissions control in the EU is largely concentrated in the industrial and waste incineration sectors. There have been a few pilot studies in Eastern Europe on mercury specific controls, as mentioned in Chapter 3. But, as yet, there is no coordinated action nor commercial impetus for these controls in the coal sector in the EU.

5.3 Comments

The EU has already seen significant reduction in mercury emissions over the last 2–3 decades due to general mercury reduction policies and the co-benefit effects of legislation on particulates, SO_2 and NOx. The installation of FGD began during the 1980s and 1990s and so the majority of plants either have FGD in place or will have within the next 3–5 years. The new legislation for coal plants, the IED, does not target mercury with strict emission limits but does introduce monitoring requirements and documents which outline the options for mercury control. This is being taken by some as an indication that emission control for mercury could be a legal requirement in future. However, the permit-based format of the EU legislation, and the option for member states to add additional control requirements, could mean that the legislation evolves on a more plant-specific basis. That is, monitoring requirements could highlight plants which have emissions of concern and these could be targeted with site-specific legislation. Conversely, the new Minamata Convention could provide impetus for the EU to move forward with more challenging mercury limits for all plants; the final outcome remains to be seen.

6 North America

The USA was the first country to move towards setting mercury specific emission limits for coal-fired plants. However, litigation and other action against the proposed regulations meant that Canada actually produced official mercury regulations before the US.

Since the markets for Canada and the USA often overlap, as discussed in this Chapter, these two countries are discussed together.

6.1 Canada

Between 1970 and 2010, Canada is reported to have reduced its mercury emissions by 90%. This was through a combination of initiatives, including (CCICED, 2011):

- The Canada-Wide Standards;
- Plant closures;
- A voluntary 'reduction/elimination of toxics' programme;
- Environmental codes of practice.

With respect to emissions from coal-fired power generation, the Canada-Wide Standard (CWS) was by far the most important initiative, but, as with all emission regulations, it was applied as one of a number of relevant pollution control initiatives, many of which would have affected mercury emissions either directly or indirectly. Table 13 shows the caps set by the CWS for individual provinces.

Table 13 Canada-wide Standard – provincial caps for 2010 (Sloss, 2012)

Province	Estimated emissions (2003-04), kg/y	2010 cap, kg/y
Alberta	1802	590
Saskatchewan	710	430
Manitoba	20	20
Ontario	495	0
New Brunswick	140	25
Nova Scotia	150	65
Total	2695	1120

The CWS was quite simple in that it specified only a cap for emissions – no instructions were given in terms of how these caps were to be achieved and no guidance was given on emission limits or BAT/MACT options.

Although the 2010 target date has passed, the CWS will continue, unchanged unless the Canadian Council of Ministers of the Environment (CCME) decide that a re-evaluation of the standards is warranted. Canada also has emission limits for SO_2 and NOx which require state-of-the-art controls and so co-benefit mercury reductions will also happen via this route.

Unlike the existing plants, new plants in Canada do have to meet stringent emission reduction requirements on a plant by plant basis, as shown in Table 14.

Table 14 Emission reduction requirements for new coal units under the CWS (Sloss, 2012)

Coal type	Capture rate, %	Emission rate, kg/TWh
Bituminous	85	3
Subbituminous	75	8
Lignite	75	15
Blends	85	3

There does not seem to be anything official published showing how the CWS has been implemented to date. It is known that Ontario planned to reduce emissions to zero through plant closure and fuel switching. However, of the remaining provinces, activated carbon appears to be the technology of choice. For example, Nova Scotia has been installing activated carbon on some plants, as have Alberta and Saskatchewan. Saskatchewan Power, the provincial utility, has installed activated carbon systems at Shand and Poplar River plants and also at Boundary Dam (Campbell, 2014). The data on activated carbon and other control technology installation rates in Canada were included with the data for the US below (*see* Figures 21, 22 and 23) but in a general manner so that no significant conclusions can be drawn on the Canadian activated carbon market other than that currently it seems healthy.

6.2 The USA

Legislation in the USA has evolved in a somewhat piecemeal manner. Recently much of the new legislation proposed by the US EPA has met with controversy and backlash, with many new rules being challenged with legislation from many different angles – some arguing that the legislation is too restrictive whilst others think it is not restrictive enough. There has been a significant amount of delay for several new rules in the USA, with some rules being thrown out completely. This means that, for the moment, many sources are somewhat confused as to what limits apply.

CSAPR – the Cross-State Air Pollution Rule – was finalised in 2011 and intended to curb emissions of particulates, SO_2 and NOx from power plants. Currently, the rule is still undergoing a re-write as a result of action in the US Court of Appeals. In the meantime, the 2005 Clean Air Interstate Rule (CAIR) continues to apply. The CSAPR aims to reduce the SO_2 and NOx which crosses between states, causing states downwind to fail to meet ground level ozone and fine particulate standards. CSAPR had trading and banking of allowances with individual state capped limits.

The Mercury and Air Toxics Rule (MATS) was promulgated in December 2011, and set MACT emission standards for a range of pollutants including fine particles, halogens and mercury. The requirements of the rule, with respect to mercury emissions, are summarised in Table 15.

Table 15 Mercury limits in the US MATS Rule (Engleman, 2014)

Source/category	Existing units			New units		
	Filterable PM	HCl	Hg	Filterable PM	HCl	Hg
Not low rank coal, lb/ BBtu	30	2	0.0012	90	10	0.0030
Not low rank coal, lb/GWh	300	20	0.0130			
Low rank coal (lignite), lb/BBtu	30	2	0.0040	90	10	0.0400
Low rank coal (lignite), lb/GWh	300	20	0.0400			
IGCC, lb/BBtu	40	0.05	0.0025	70	2	0.0030
IGCC, lb/GWh	400	5	0.0300			

BBtu billion Btu; Btu British thermal unit

The values in the table are shown in US units. Conversion to metric values such as µg/m^3 requires assumptions which may incur errors. And so direct comparison of this limit with limits elsewhere is not simple. However, the challenge posed by these limits may be made clearer by regarding the 0.0012 lb/Btu limit for existing units as requiring 80–85% mercury reduction for most US coals. For new units, the 0.030 lb/Btu value means a 95% reduction in mercury. This is clearly a challenging set of limits. It is estimated that the MATS rule will result in a mercury reduction from electricity generating units from 28.7 t/y to 6.6 t/y once it is fully implemented.

The limits specified in the MATS rule apply to existing units in April 2015, although some plants are seeking a 1 year extension. The latest data suggest that, of 145 units have extensions, which amounts to around 1/3 of the fleet (NACAA, 2014). Over and above the requests for delay on starting retrofits, some plants may need extensions to allow time to complete upgrades. Although activated carbon systems can be installed in under 18 months, full FGD systems may take at least 3–4 years from planning to completion. The requirement for labour and equipment work on upgrades under MATS was reported to 'exceed historical industry maximum by 51–162%' and this was/is expected to lead to the requirement for extensions on the MATS deadlines for further plants (PowerNews, 2012).

Figure 21 shows the mercury emissions from the 100 largest emitting coal-fired plants in the USA (2012 values). Comparison of the emission rates (0.01 to over 0.08 lb/GWh) shows how challenging the 0.013 lb/GWh limit will be for these plants. Beasley and others (2013) describe MATS as 'one of the US EPA's most expensive regulations'. The US EPA estimates the cost of compliance with MATS at $9.6 billion. However, together the MATS and CSAPR are estimated to provide $150–380 billion in health benefits, including lower numbers of premature deaths, asthma attaches and so on.

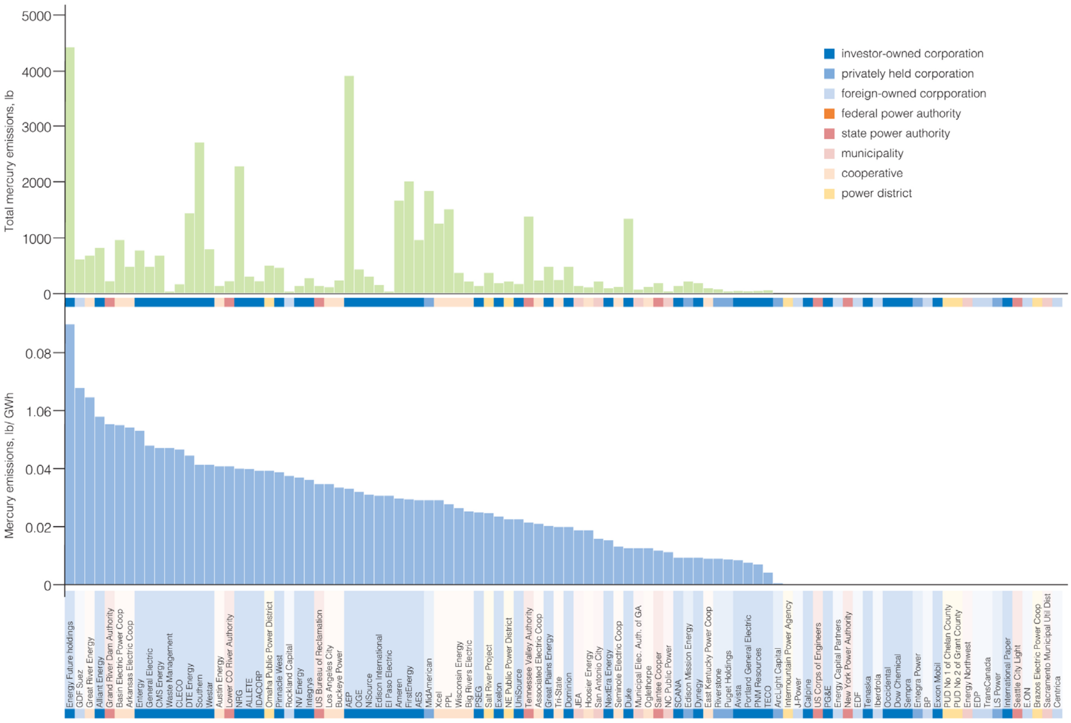

Figure 21 Coal mercury emissions (lbs) and emission rates lb/GWh) from top 100 US coal plants (2012)

But there is more to MATS than just the mercury limits. MATS includes work practice requirements aimed at improving plant efficiency, which reduces emissions of all pollutants simultaneously. For most plants this will be achieved through combustion modifications, which also serve to reduce NOx emissions. Spinney (2014) uses real plant data to show how neural net combustion optimisation programmes can be used to improve plant combustion efficiency, including the operation of low NOx burners and reducing the reagent cost for SNCR systems, arguing that such online modelling systems can pay for themselves within a year.

6.2.1 Changes in fuel use

The combination of all the rules hanging over coal-fired power generation poses a challenge to many plants in terms of the cost required to remain in compliance. For many older plants, the cost is simply prohibitive. Most coal-fired plants in the USA are over 30 years old and some are over 50 years old. The US DOE has projected that around 20% (60 GW) of existing plants in the US will retire by 2018. Of this, 10 GW had retired by 2012. For example, the Tennessee Valley Authority is retiring 8 units totaling 3 GW, South Carolina Electric and Gas is closing the 295 MW Canadys Station, Consumers Energy plans to close three plants in Michigan, Energy Capital is closing Brayton point (1 GW) and Georgia Power is closing the 155 MW Mitchell facility (Patel, 2014). Dayton Power and Light plans to retire 6 units, totaling 290 MW at the Hutchings site in Miamisburg, Ohio by 2015. Plans have been filed to replace at least some of the capacity with gas. The reason cited was quite simply 'it is not economical to install controls on those units to comply with MATS' (Patel, 2013).

The decision on whether to retire a coal plant is not made lightly. In addition to the compliance issues and related costs, external factors such as gas prices and electricity demand must also be taken into account (Engelman, 2014).

The limits for new plants are also challenging, effectively requiring that any new coal-build is fitted with the entire suite of state-of-the-art control technologies. This will be costly and the cost of a new coal plant may be more than that of a new gas plant in most areas. There is also the suggestion that, in addition to gas taking favour over new build, some existing coal plants are switching to be gas-fired units. For example, the 427 MW IPL unit of AES Corp in Indianapolis is switching from coal to gas by the end of 2016, along with several moves in other units. The company is moving from 87% coal in 2007 to 44% in 2017 (Tomich, 2014).

6.2.2 Co-benefit options

The SO_2, NOx, halogen and fine particulate emission limits in MATS will require that most plants have state of the art control technologies for acid gases and particulates. This will clearly have significant co-benefit effects for mercury. Since MATS relates to multiple emission controls, plant operators are making decisions on the future of their plant based on compliance with all the requirements and not just mercury. Control technologies which purport to reduce emissions of several pollutants simultaneously may be considered more cost-effective than a series of individual technologies to cope with different pollutants in turn.

The Energy Information Administration published a chart which implied that almost 70% of the fleet is already in compliance, due to having FGD already installed and that 7% would comply using either FGD or DSI (dry sorbent injection, such as activated carbon) (EIA, 2014). However, the data were somewhat misleading in that FGD alone is not enough for the majority of US plants to meet MATS requirements. There is a significant amount of investment ongoing in terms of mercury specific controls and most of the plants which have FGD may still require the use of additional oxidants or sorbents to ensure that the mercury capture is maximised. The FGD forms a major part of the compliance strategy but will not be sufficient on its own. As the sections to follow show, the market for additives (oxidants and sorbents) to maximise mercury capture in existing pollutant control systems in the USA is significant and growing.

6.2.3 Mercury specific controls

Since the MATS legislation is challenging, many coal-fired power plants have little option other than to look at installing mercury specific controls. There is clearly a market developing rapidly, as summarised in the paragraphs to follow. However, MATS compliance will not be effective until April 2015 or 2016 (depending on plant age, location and individual state requirements). While some plants may already have committed to a certain type of control system, many others are still at the decision stage. Many are currently testing their options via slip-stream studies or short-term full-scale demonstration projects. In almost all cases, this information remains proprietary for both the utility and the company supplying the control technology. So, for the moment, the sections below can only give an indication of a market that is still relatively fluid.

The Institute of Clean Air Companies (ICAC) keeps a record of the activities being carried out by member companies. Their database of mercury control systems gives an impressive record of all the projects planned or underway. Unfortunately the database only reflects the information provided by member companies and so therefore may be missing some data from companies which are not members. However, it would appear that most of the major mercury control companies are members of ICAC. According to the ICAC database for 2013, activated carbon is being applied at up to 91 GW of plants in the USA and Canada. Of these around 41 GW are subbituminous plants, 35 GW are bituminous, 10 GW are PRB and 5 GW are lignite. According to Power Engineering (2013a) the activated carbon market in the USA will exceed $4 billion by 2019, more than doubling from the value of $1.91 billion in 2012. Powdered activated carbon makes up around 49% of the current activated carbon market.

The activated carbon market in the US seems strong and growing stronger, with many commercial companies expanding successfully. For example, Cabot Norit Activated Carbon, is a market leading PAC supplier to coal-fired utilities in the US, especially the DARCO® Hg family of activated carbon products and injection equipment. As of September 2014, over 23 GW of coal-fired power in North America were using Cabot Norit technologies (*see* Figure 22). The company has commented that the impending implementation of the EPA’s new mercury removal standards is expected to drive further growth for activated carbon solutions as utilities upgrade their coal-fired power plants to comply with the regulations. Cabot is also optimistic that they will continue to see significant increases in the consumption of their products in the future (Krents, 2014).

Figure 22 Activated carbon silo (Krents, 2014)

ADA Carbon Solutions is a market-leading supplier of activated carbon for mercury control, supplying about 30 GW of current North American power plants with their PowerPAC® and FastPAC™ activated carbons. They have a number of long-term contracts for the supply of activated carbons for mercury control. Some sites have been utilising their products since 2009-10 to maintain mercury compliance with state rules and consent decrees (Glesmann, 2014).

Figure 23 shows the installed capacity (MW) of coal-fired utilities in Canada and regions of the USA which have activated carbon systems either in place or planned. These data, provided by ICAC (Institute of Clean Air Companies, ICAC, 2014), only include information from companies which are members of ICAC and are therefore not complete. That aside, the major activated carbon companies are included – ADA-ES, B&W, Clyde Bergmann, Norit Americas, Albemarle, SMCR, Siemens Environmental Systems, BPI, Dustex, and SPE-Amerex, amongst others.

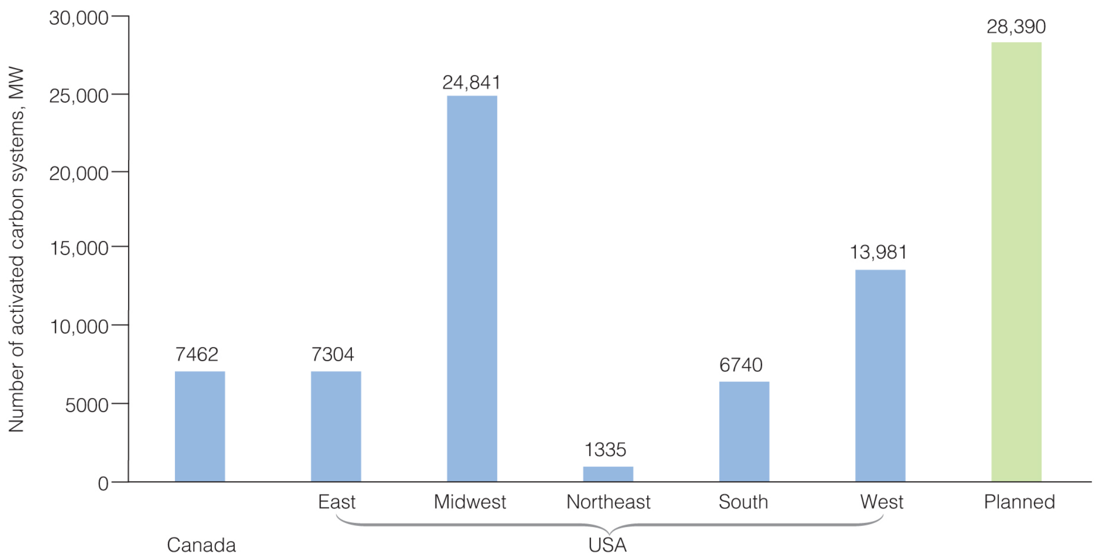

Figure 23 Activated carbon systems installed or planned in the USA and Canada (ICAC, 2014)

Figure 24 shows data from the same study but expressed in terms of the number of units with activated carbon systems installed. The majority of these systems are in the Midwest which is where the majority of the coal-fired plants are located. These charts gives an indication of just how many plants are installing activated carbon in response to the MATS and CSAPR. ICAC's August 2014 market study, authored by Andover Technology Partners, projects activated carbon demand for the coal-fired utility market (MATS-driven) based on different assumptions on control strategy, including scrubber use. Once MATS is fully implemented the annual range is ~300 to ~900 Mt/y. The same study forecasts a possible (realistic) scenario of activated carbon demand of 400–500 Mt/y for 2015-17 on an installed base of 140–150 GW.

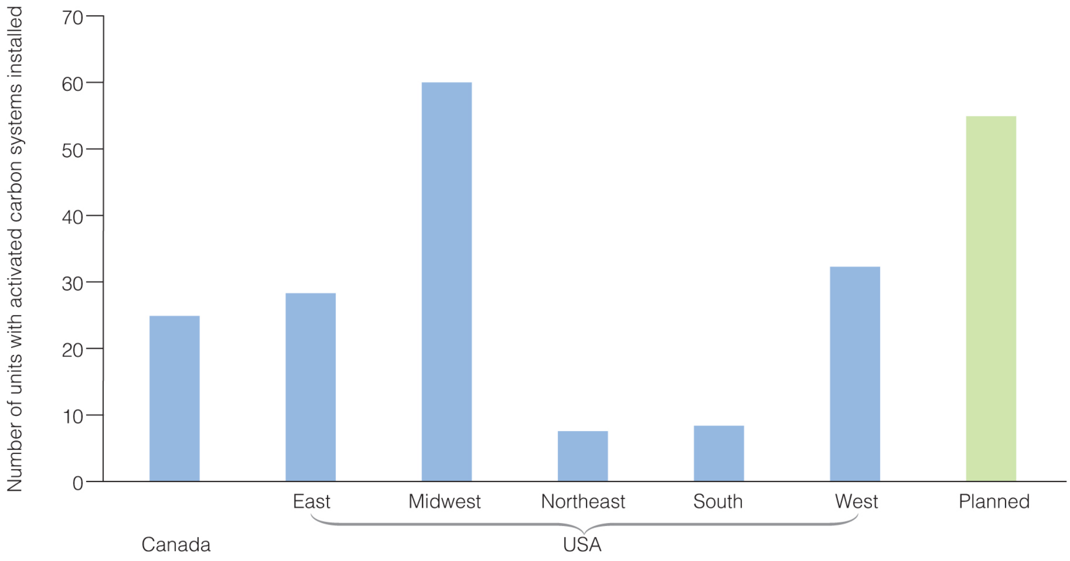

Figure 24 Activated carbon installed (by region) or planned in the US and Canada, as of April 2013 (ICAC, 2014)

Figure 25 gives the information on the spread of the activated carbon systems across plants firing different coal types.

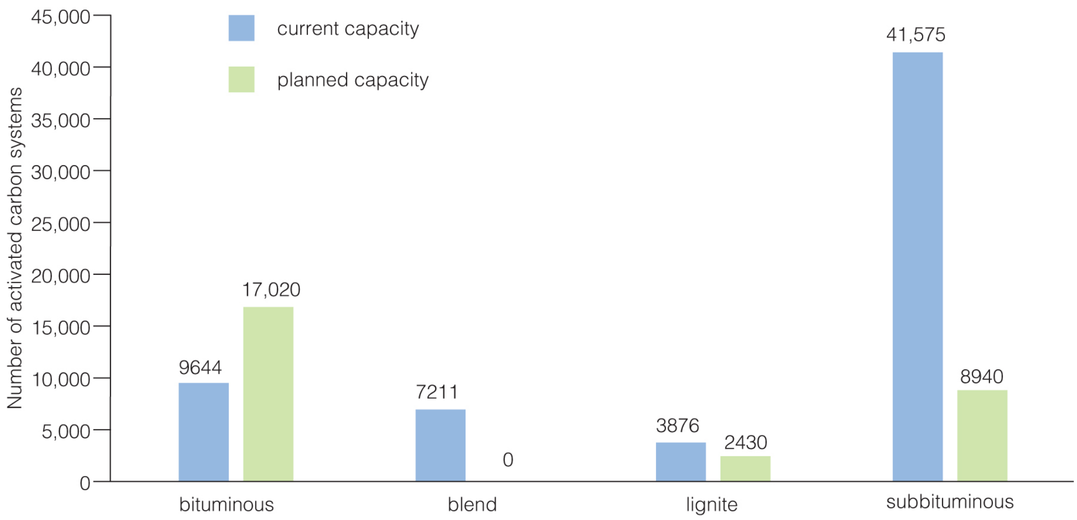

Figure 25 Activated carbon systems for mercury control in place (or under construction) and planned for the USA and Canada, MW (ICAC, 2014)

As shown in Figure 25, the majority of activated carbon systems are in place on subbituminous plants with a total of 41,575 MW (representing 101 units) with a further 8940 MW (19 units) with systems planned for the near future. There are 35 bituminous plants (9644 MW) with ACI installed and a further 33 units (larger plants, totalling 17,020 MW) planned. Eight lignite units (totalling 3876 MW) have ACI in place and a further 3 (totalling 2430 MW) are planned. However, although 16 units (totalling 7211 MW) firing blended coal already have ACI in place or under construction, there do not appear to be any further ACI systems planned for blended units. Again, however, it is important to note that these data are incomplete and are to be used to gauge an idea of the relative spread of ACI systems across unit types rather than a definitive summary of all that is happening in the sector.

Figure 26 shows the installation rate of sorbent and oxidant based mercury controls at US plants firing challenging coals, as supplied by ICAC members, as of 2013 (Glesmann, 2014). Note that this slide should not be taken as a literal and exact representation of the current additive based market but rather as an indication of trends in the market for different coal types. For example, the chart suggests that, for lignite plants, the Cyclean and M45 technologies are most popular whereas the KNX/KNZ methods were most widely used at plants firing subbituminous coals. However, since the collation of these data, KNX/KNZ has lost a patent contest with Nalco and has been removed from the market. As mentioned before, these oxidant approaches are most effective on subbituminous and lignite coals but there is also a driver for some plants to use approaches such as Cyclean due to specific tax code benefit in the US which apply to technologies which are regarded as renewable (Glesmann, 2014).

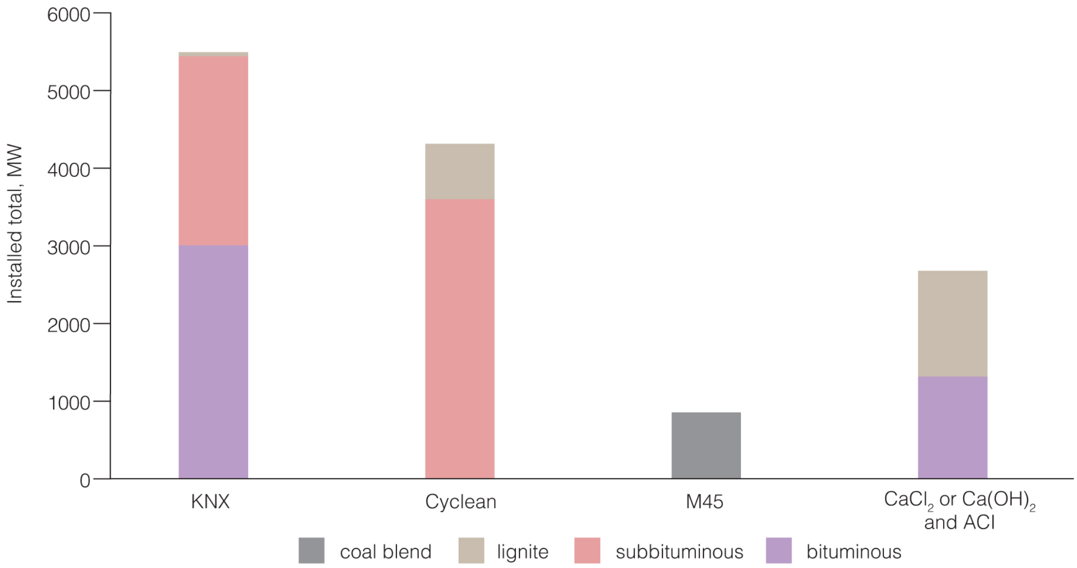

Figure 26 Installation of additive based mercury control systems for challenging coals in the USA, 2013 (based on ICAC data provided via Glesmann, 2014)

Beasley and others (2013) looked at the way coal plants may choose to comply with emission limits in the US under different scenarios. The scenarios were relatively complex ranging from baseline (excluding CSAPR and MATS) to quite advanced options such as MATS with SCR and MATS with CO_2 (including a CO_2 tax). The interested reader is referred to the original document for more details. The study showed that, under the different scenarios, the requirement for new FGD over the baseline) could be anywhere from very little up to 77 GW (assuming all plants meet MATS requirements for acid gases). Dry FGD systems could increase by up to 94 GW if all plants meet the MATS requirements. SCR capacity could increase by 150 GW by 2020 if all plants are required to meet the NOx scenarios under the National Ambient Air Quality Standards. The capacity of installed ACI could increase by around 200 GW if MATS is met, but with no-plants opting for dry sorbent injection. Fabric filters would also increase by 160 GW under this assumption. The paper by Beasley and others (2013) is complex and hard to do justice to in this review, but it is clear from the paper that, although significant retrofitting of flue-gas cleaning technologies is inevitable in the USA, the actual distribution of the different control options in the marketplace will be dependent on how the rules are interpreted and applied in practice.

6.2.4 Multi-pollutant systems

As discussed in Chapter 3, there are many multi-pollutant systems being developed which can reduce mercury whilst lowering emissions of other pollutants. The Airborne, NeuStream™ and Skymine technologies discussed in Section 3.3 have all been tested at pilot scale but are not yet proven at full scale. However, all of the development of these systems is currently taking place in the USA and it is likely that this is where the initial market will be. That said, there is at least some tentative, pilot scale movement of multi-pollutant technology from the US to the Chinese market, as discussed in Chapter 4.

6.3 Comments

Since the USA and Canada have been the first countries to set strict mercury emission reduction requirements on coal-fired plants it is not surprising that this is where the vast majority of the control technology market is emerging. Plants in the US still have a year or so to decide how they plan to comply with MATS. However, MATS sits as only one of a number of regulations which limit a combination of pollutants and so plant managers are deciding on emissions controls for several pollutants simultaneously. In some cases, all emission limits could be achieved using existing pollution control equipment. However, in many more cases, modifications are required, such as the addition of oxidants or sorbents, to ensure that the limits for mercury are not exceeded. There is a vast market emerging in North America for activated carbons and, to a slightly lesser extent, oxidants.

Some plants do not have technologies already in place which offer co-benefit effects or these technologies are old and inadequate. In these situations the plants have an almost open book choice of how best to achieve compliance. However, the method chosen to achieve compliance will be made taking into account the requirements for the control of several different pollutants simultaneously. And cost will be important. It is in these more challenging plants, and on new plants, where the choice is not restricted by any existing plant format, the market for sorbents and multi-pollutant strategies will be greatest.

7 Conclusions

Mercury control technologies are being developed and a market is evolving as a direct result of tightening emission limits in North America. These mercury control systems are emerging into an already existing market for technologies which control pollutants such as particulates, SO_2 and NOx. Many plants already have control technologies for these other pollutants and, since these can have a co-benefit effect on mercury control, this effect is taken into account when plant operators consider how best to comply with new mercury limits. As much as possible, operators want to take advantage of as much free mercury control as they can achieve. If the existing systems are not adequate to bring the mercury down to prescribed limits, then they will be optimised – this can mean changes in fuel mix, the addition of oxidants, a change in catalyst in SCR systems or the addition of activated carbon. It would seem that around 70% of coal-fired plants in the US will achieve MATS compliance through this approach. Countries such as Korea, Japan and member states of the EU may not have strict mercury legislation as yet, but are also seeing significant mercury reduction as a result of co-benefit effects of existing control technologies.

In US plants where the existing control technologies are not able to achieve the level of mercury control required under the new MATS legislation, mercury-specific technologies are required, for example:

- at plants which do not have systems such as FGD in place to offer co-benefit effects;
- at plants with the co-benefit effects are not achieving the mercury reduction rate required. This may be due to the mercury chemistry or to aging or malfunctioning pollution control systems; or
- at plants firing challenging coals such as PRB and lignite.

For these sources, there is a market emerging for more advanced systems of mercury-specific techniques such as the application of oxidants and sorbents. There is also a new market emerging for multi-pollutant control technologies – systems which control the emissions of several pollutants simultaneously. Mercury specific and multi-pollutant control systems will find much of their market in new or total rebuild plants where the choice of control technologies is completely open and where capturing as many pollutants in the one system makes more economic and practical sense than bolting on control technologies for individual pollutants one by one. Multi-pollutant technologies are relatively new and, in many cases, still at pre-commercial scale.

The mercury control market is by far the strongest in Canada and North America simply because these are the only regions which currently have legal requirements for mercury control. However, the new UNEP Minamata Convention on mercury could stimulate new control requirements or the tightening of existing requirements in other regions. The EU has established new guidelines for monitoring and BAT control of mercury and this could mean that plants in the region will face more strict permitting requirements in the future. China's existing legislation on mercury is not challenging but it would appear that the mercury control technology market is about to arrive in the country and it could be immense. Although little has been published, it is known that several technologies, from activated carbons through to multi-pollutant control systems, have been tested at pilot scale at some plants in China.

As in North America, the EU and Chinese markets will develop depending on what the legislation requires. If the existing co-benefit effects in these regions (which are significant) are not enough, then a new mercury-specific market will emerge. When it does so, those companies which have proven themselves in North America should be ready to move in to this new market region. The market will be similar to that in North America in that those plants with existing co-benefit options may maximise these with oxidants and sorbents. However, the growth rate in coal use in China, and the rapid installation of new plants, means that the market for multi-pollutant control systems in China could be the largest in the world.

How markets will potentially emerge in other countries in response to the Minamata Convention will depend on the level of commitment – that is, how much control or reduction is deemed necessary or achievable in each region. Some regions, especially those with economic, geographical or other challenges, may maximise the cost-effectiveness of co-benefit effects. Others may choose to aim for greater reduction and will therefore create new market regions for activated carbons and sorbents.

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