



**UNITED NATIONS  
ENVIRONMENT PROGRAMME**



Chemicals Branch, DTIE

Study on mercury-emitting sources, including  
emissions trends and cost and effectiveness of  
alternative control measures  
“UNEP Paragraph 29 study”

Zero Draft report  
2010-03-04

Contributing authors;

John Munthe, Karin Kindbom, Jenny Arnell, IVL Swedish Environmental Research Institute,

Jozef Pacyna, Kyrre Sundseth, Elisabeth Pacyna, NILU

Damian Panasiuk, NILU PL,

Simon Wilson, AMAP

Peter Maxson, Concorde East/West

## Table of contents

<b>1.</b>	<b>Introduction .....</b>	<b>6</b>
1.1.	Background, Scope and Mandate .....	6
1.2.	Sources of information .....	6
<b>2.</b>	<b>Global emissions of mercury and future scenarios.....</b>	<b>8</b>
2.1.	Global anthropogenic mercury emissions to air .....	8
2.2.	Trends in global mercury emissions to air.....	11
2.2.1.	Emissions by geographical region .....	12
2.3.	Scenarios for global mercury emissions to air.....	14
2.3.1.	Basic principles.....	14
2.3.2.	Scenario descriptions .....	15
<b>3.</b>	<b>Emission control, efficiencies and costs .....</b>	<b>18</b>
3.1.	Emission control .....	18
3.1.1.	General primary control measures.....	18
3.1.2.	Technical co-control of air pollutants and mercury .....	19
3.2.	Combining different control technologies for optimised mercury control.....	20
3.3.	Cost and efficiencies for mercury control .....	21
<b>4.</b>	<b>Characterisation of the selected sectors.....</b>	<b>23</b>
4.1.	Coal combustion in power plants and industrial boilers.....	23
4.1.1.	Origin of mercury and emissions from coal combustion.....	23
4.1.2.	Technologies for coal combustion.....	23
4.1.3.	Control measures in coal combustion .....	24
4.1.4.	Costs and efficiencies of control technologies for coal fired power plants .....	27
4.2.	Non ferrous metal production.....	30
4.2.1.	Origin of mercury and emissions from non-ferrous metal production .....	30
4.2.2.	Technologies for non-ferrous metal production .....	31
4.2.3.	Control measures in non-ferrous metal production .....	32
4.2.4.	Costs and efficiencies of control technologies for non ferrous metal production. ....	32

4.3.	Cement production .....	34
4.3.1.	Origin of mercury and emissions from cement production .....	34
4.3.2.	Control measures in cement production .....	35
4.3.3.	Costs and efficiencies of control technologies for cement production .....	36
4.4.	Waste incineration .....	37
4.4.1.	Origin of mercury and emissions from waste incineration .....	37
4.4.2.	Technologies for municipal solid waste incineration .....	38
4.4.3.	Control measures in waste incineration .....	38
4.4.4.	Costs and efficiencies of control technologies for waste incineration.....	39
<b>5.</b>	<b>Summary and plans for second phase of study.....</b>	<b>43</b>
5.1.	Summary.....	43
5.2.	Continuation of the Para 29 study .....	43
<b>6.</b>	<b>References: .....</b>	<b>46</b>

DRAFT

## Note:

This Zero Draft report provides a summary of available knowledge on mercury emissions to air; short description of the sectors selected for this study; where mercury enters the processes and where/how it is released to air; control options and the associated costs. It is based on reports on global mercury emissions and qualitative assessment of costs and efficiencies of control options, prepared for UNEP in 2008, as well as recent information available from the open literature on emissions, control options and costs.

This Zero Draft report also contains an overview of future scenarios for mercury emissions and initial assumptions to be used in the preparation of scenario calculations during Phase 2 of the study.

In Phase 2 additional information will be collected in order to refine and revise the information presented here. Questionnaires and electronic spreadsheets have been prepared to submit information. In the questionnaires, the countries are invited to report on the technical specifications of the selected sectors either as country averages or on an individual plant basis. The request for information also asks for information on current and planned implementation of control measures for air pollutants, restructuring and modernisation of the sectors. The collected information will be compiled in the spring of 2010 to provide for a more accurate basis for development of improved estimates and scenarios on emissions, better source characterization and improved estimates of control costs and efficiencies.

The intention with the Zero draft report is not to provide direct input to the intergovernmental negotiating committee at this stage but rather to inform countries and individuals involved in the UNEP mercury activities on status of information currently available for calculating costs and efficiencies for mercury emission reduction strategies. It should also serve as a guide for those countries involved in the Paragraph 29 study on the type of information needed, and why this information is necessary for more detailed and accurate scenario calculations.

## List of abbreviations

AMAP	Arctic Monitoring and Assessment Program
BAT	Best Available Technology
BREF	Best Available Technology Reference Documents
By product emissions	Emissions occurring from sources where mercury is a contaminant in fuel or raw material used in the process.
CCC	Clean Coal Centre of the IEA
CO	Carbon monoxide
ESP	Electrostatic Precipitator
ESPREME	Integrated Assessment of heavy metal releases in Europe. Research project funded by European Union
EU	European Union
EU-27	The 27 member states of the European Union
EXEC	Extended Emissions Control scenario
FBC	Fluidized Bed Combustion
FF	Fabric Filter
FGD	Flue Gas Desulphurization
HEIMSTA	Research project funded by European Union.
Hg <sup>0</sup>	Elemental mercury
HgCl <sub>2</sub>	Mercuric Chloride
IEA	International Energy Agency
INC	Intergovernmental Negotiating Committee
Intentional use emissions	Emissions occurring from sources where mercury is intentionally used e.g. in products or as a part of an industrial process.
IPPC	Integrated Pollution Prevention Control, a EU directive
LRTAP Convention, CLRTAP	Convention on Long-Range Transboundary Air Pollution. A convention on air pollution under the UN Economic Commission for Europe (UN ECE)
MFTR	Maximum Feasible Technical Reduction scenario
NH <sub>3</sub>	Ammonia
NO <sub>x</sub>	Nitrogen Oxides
PCC	Pulverized Coal Combustion
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO <sub>2</sub>	Sulphur Dioxide

SQ        Status Quo scenario  
VOC      Volatile Organic Carbon

DRAFT

# 1. Introduction

## 1.1. *Background, Scope and Mandate*

As called for in paragraph 29 of decision 25/5 III of the Governing Council/Global Ministerial Environment Forum of the United Nations Environment Programme (UNEP), a study is being undertaken on the various types of mercury-emitting sources and current and future trends in mercury emissions, including an analysis and assessment of the cost and the effectiveness of alternative control technologies and measures.

The purpose of the study is to inform the work of the intergovernmental negotiating committee (INC) and, as such, to give background information relevant to the development of measures for controlling mercury emissions that could be featured in the legally binding instrument that is to be elaborated.

The main objectives of the study are:

- (a) To present updated and new information on mercury emissions for selected countries and sectors and current trends in mercury emissions;
- (b) To provide an overview of the technical characteristics of the main sources of mercury emissions in important sectors in the selected countries;
- (c) To provide an overview of current and planned initiatives and measures at the national, regional and global levels and how they may affect future mercury emissions. This includes initiatives directed to mercury, air pollution abatement and carbon dioxide abatement;
- (d) To provide quantitative information on the effectiveness and costs of relevant and representative abatement measures in the selected sectors.

The study will focus on the largest emission source categories identified on the basis of previous UNEP emissions reports and information available from the open literature and for which information on costs and effectiveness of alternative control technologies and measures may be available and informative for the INC. These priority sources are coal-fired power plants and industrial boilers; non-ferrous metal production (in particular lead, zinc, copper and gold); waste incineration; and cement production. The selected sectors all emit mercury from high temperature processes at large point sources. These characteristics imply common approaches to control mercury emissions to air.

The study will use information from countries that have significant mercury emissions in each of the source categories. The selected countries for the study are Brazil, China, India, the Russian Federation, South Africa, the United States of America and the 27 countries of the European Union. The results will be extrapolated to provide global estimates and presented in the form of a series of different mercury control scenarios providing a range of emissions reductions at different estimated implementation costs.

The project will be conducted in two phases where this report represents the results of Phase 1: The Zero Draft Report.

## 1.2. *Sources of information*

This Zero Draft report is mainly based on two reports prepared in 2008; the Global Mercury Emission Inventory for 2005 (prepared in cooperation between UNEP and AMAP,

[http://www.chem.unep.ch/mercury/Atmospheric\\_Emissions/Technical\\_background\\_report.pdf](http://www.chem.unep.ch/mercury/Atmospheric_Emissions/Technical_background_report.pdf)) and “A general qualitative assessment of the potential costs and benefits associated with each of the strategic objectives set out in Annex 1 of the report of the first meeting of the Open Ended Working Group” available at:

[http://www.chem.unep.ch/mercury/OEWG2/documents/e52/English/OEWG\\_2\\_5\\_add\\_1.pdf](http://www.chem.unep.ch/mercury/OEWG2/documents/e52/English/OEWG_2_5_add_1.pdf)

Additional information on control technologies was taken from the open literature and results from EU projects such as ESPREME and HEIMSTA.

DRAFT

## 2. Global emissions of mercury and future scenarios

### *Purpose of section*

To provide an overview of the global anthropogenic emissions of mercury, both as total emissions and from the selected sectors and geographical regions.

### *Sources of information available for the zero draft text:*

UNEP/AMAP report (2008): “Technical Background Report to the Global Atmospheric Mercury Assessment” with updates from the on-going AMAP Arctic Mercury Assessment.

### *Status of information:*

Currently best available knowledge

### *Anticipated improvements to be made in final Paragraph 29 study report*

New information provided by the selected countries through the questionnaires will permit improved estimates of emissions from selected sectors in the selected countries, to be used as a basis for the development of scenarios for emissions, emission controls and costs as well as for global extrapolation.

### **2.1. Global anthropogenic mercury emissions to air**

An inventory of the global anthropogenic emissions of mercury for 2005 was prepared in a joint UNEP/AMAP project in 2008. Details on the methods, data sources and other information can be found in

[http://www.chem.unep.ch/MERCURY/Atmospheric\\_Emissions/Technical\\_background\\_report.pdf](http://www.chem.unep.ch/MERCURY/Atmospheric_Emissions/Technical_background_report.pdf).

The 2005 inventory addressed ‘by-product’ mercury emissions to air from main energy production and industrial sectors and estimates of emissions associated with a number of ‘intentional-use’ sectors. ‘By-product’ sectors include: stationary combustion of fossil fuels in power plants and for residential heating; pig iron and steel production; non-ferrous metal production; cement production; mercury production; large scale gold production; and certain ‘other’ activities. Mercury emissions from the chlor-alkali industry are also accounted in the ‘by-product’ sector inventory. Intentional-use sectors include artisanal and small-scale gold mining; emissions from dental use of mercury associated with cremations; secondary steel production; diffuse releases from product use, and waste disposal (including waste incineration).

Stationary combustion of coal is the largest single source category of anthropogenic mercury emission to air, represented in Figure 1 by coal combustion in power plants and by residential and other combustion. Mercury is present in coal as a minor constituent which is released to air during combustion. Combustion of other fossil fuels for energy or heat production, contribute to mercury emissions but to a significantly smaller extent than coal.

Mining and industrial processing of ores, in particular in primary production of iron and steel and non-ferrous metal production (especially copper, lead and zinc smelting), release mercury as a result of both fuel combustion and mercury present as impurities in ores. Metal production

sources of mercury also include mining and production of mercury itself (a relatively minor source) and production of gold, where mercury is both present in ores and used in some industrial processes to extract gold from lode deposits. Use of mercury to extract gold in artisanal and small-scale gold mining operations is an intentional use also giving rise to large emissions both to air and to water. Water emissions are in this case larger than the air emissions and may result in significant environmental impacts on the local scale.

The third major source of 'by-product' releases of mercury is associated with cement production, where mercury is released as a result of the combustion of fuels (mainly coal but also a range of wastes) to heat cement kilns and from mercury contained in the raw material (limestone etc) and additives.

Other sources included in the UNEP/AMAP (2008) inventory are caustic soda production (chlor-alkali industry), mercury production, gold production (large scale and artisanal), waste incineration and other waste disposal, cremation and diffuse releases from product use.

The estimated global anthropogenic emissions of mercury to air in 2005 from the various sectors are presented in Table 1 and Figure 1.

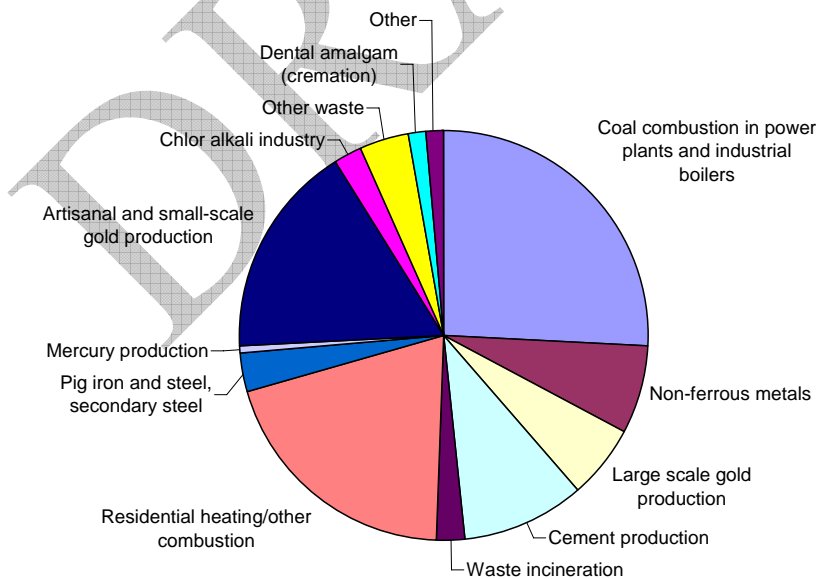
In Table 1 the emissions and the relative contribution to global mercury emissions to air in 2005 from the selected sectors for this study are presented in the top five rows. Coal combustion in power plants contributed 26 percent to global emissions, non-ferrous metal production 7 percent, large-scale gold production 6 percent, cement production 10 percent and large scale waste incineration 2 percent. The total emissions of mercury from the waste sector (i.e. including small scale burning, emissions from waste land-fills) represent an additional 4 % of the global total. These sectors were prioritised due to their respective relative contribution to global emissions of mercury to air, and as being sectors largely consisting of point sources with high temperature combustion or processes where installation and use of similar technical emission control equipment is feasible.

**Table 1.** *Estimated global anthropogenic emissions of mercury to air in 2005 from various sectors (revised from UNEP/AMAP, 2008).*

	<b>Emissions in 2005*</b>	<b>% of total</b>
	<b>tonnes</b>	
Coal combustion in power plants and industrial boilers	498	26
Non-ferrous metals	132	7
Large scale gold production	111	6
Cement production	189	10
Waste incineration	42	2
Residential heating/other combustion	382	20
Pig iron and steel, sec. steel	61	3
Mercury production	9	0.5
Artisanal and small-scale gold production	323	17
Chlor alkali industry	47	2
Other waste	74	4
Dental amalgam (cremation)**	27	1
Other	26	1
<b>Total</b>	<b>1921</b>	

\* Represents best estimates. See UNEP/AMAP (2008) for discussion on uncertainties.

\*\* Does not include other releases from production, handling and disposal of dental amalgam.



**Figure 1.** *Proportion of global anthropogenic emissions of mercury to air in 2005 from various sectors (revised from UNEP/AMAP, 2008).*

The global inventory of anthropogenic emissions to air for 2005, described in UNEP/AMAP (2008) and summarized in UNEP (2008) was the most comprehensive such inventory presented to date. A revision was undertaken in 2010, which for 2005 resulted in only small changes in the global total emissions of mercury to air. This is further described in chapter 2.2 below.

The selected sectors for this study are coal combustion in power plants and industrial boilers, non-ferrous metal industry (incl. large scale gold production), cement industry and municipal waste incineration. The emissions from the selected sectors represent 51 percent of the total emissions to air in 2005.

Combustion of fossil fuels in power plants and industrial boilers is estimated to contribute to about 26 percent (498 tonnes) of the total global mercury emissions to air in 2005. An additional 382 tonnes of mercury (20 percent of global emissions) are estimated to be emitted from fossil fuel combustion for residential heating (UNEP/AMAP, 2008, AMAP, 2010). Residential heating, although a significant source is not further covered in this study which is focussed on possibilities to control emissions from major point sources and thus only covers emissions from power plants and industrial boilers.

Non-ferrous metal industries are estimated to contribute to about 7 percent (132 tonnes) of the total mercury emissions to air worldwide in 2005. China emits 50 percent of the sector emissions, followed by South Korea, Chile, and Australia, - emitting 5 percent each (see chapter 2.2. for further detail on emissions by geographical region). Almost 70 percent of the total mercury emissions from non-ferrous industries originate in Asia. Large-scale gold production represents 6 percent of the global emissions (111 tonnes). The largest emitter is China with 40 percent of the sector emissions, followed by Australia, the United States and Indonesia all contributing between 7 and 5 percent of the sector emissions.

About 189 metric tonnes (10 percent) of the total emissions of mercury emitted to air from anthropogenic sources worldwide in 2005 originated from the manufacture of Portland cement. It is estimated that Asia emits about 74 percent of the total mercury emitted from the sector. China is by a large margin the main contributor, responsible for 45 percent of total emissions to air from cement manufacturing followed by India (6 percent), Japan (5 percent) and the United States (3 percent) (UNEP/AMAP, 2008).

Incineration of municipal solid waste is estimated to contribute approximately 2 percent of the global mercury emissions to air. North America, mostly because of the U.S., contributes about 43 percent of the mercury from waste incinerated worldwide. Europe is responsible for somewhat less than 30 percent, while Asia is responsible for 16 percent. The larger individual source countries, following the US, are Japan, Russia and Germany, all contributing 10 percent each to the worldwide emissions from waste incineration.

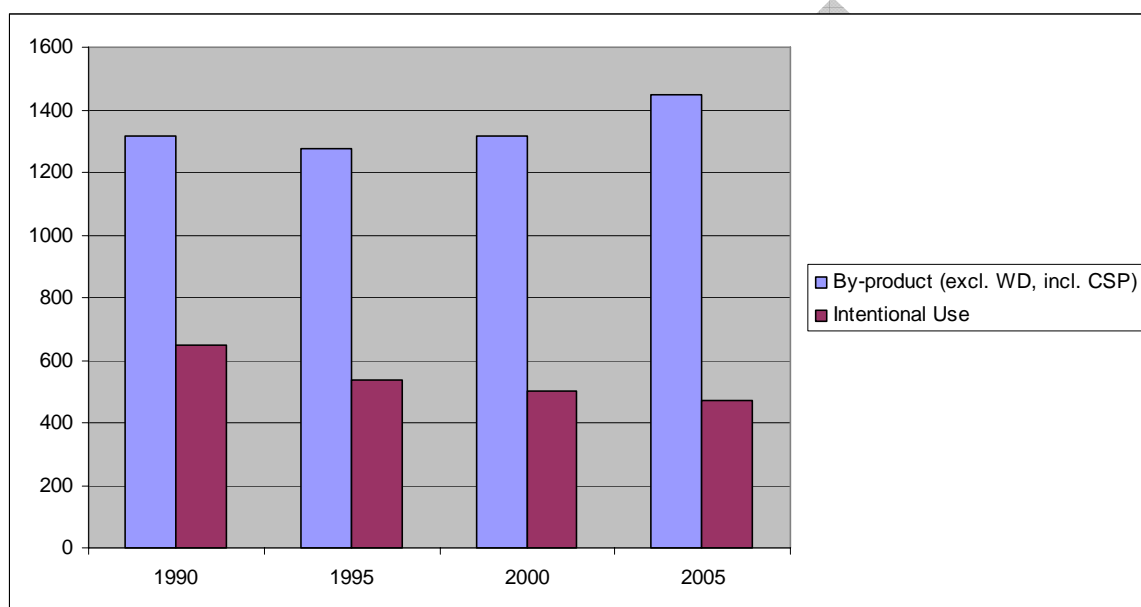
## **2.2. Trends in global mercury emissions to air**

As part of its 2010 assessment of mercury in the Arctic, the Arctic Monitoring and Assessment Programme (AMAP) undertook a re-analysis of global mercury inventories from 1990, 1995, 2000 and 2005 (Pacyna and Pacyna, 2002; Pacyna and Pacyna, 2005; Pacyna et al., 2006) in an attempt to prepare a series of more comparable historical global emission inventories and to allow an analysis of global trends in mercury emissions to air. This re-analysis employed a common methodology, a more consistent information base for estimating certain emissions, and updating of the earlier inventories for various countries and sectors to account for improved knowledge gained during the process of preparing the inventories over the last 15 years. It also

involved further revising the 2005 inventory for newly available data on regional mercury consumption that form the basis for estimates of emissions associated with ‘intentional-use’ sectors.

For 2005 the revision resulted in an estimate approximately 5 tonnes lower, or 1921 tonnes compared to the 1926 tonnes of global mercury emissions to air estimated in the UNEP/AMAP (2008) report. In addition to revising the emissions from the ‘by-product’ sector for all years (1990, 1995, 2000 and 2005), the re-analysis also included estimates of emissions from ‘intentional use’ of mercury for the years 1990, 1995 and 2000, which were previously not available.

Revised estimates of emissions of mercury to air in 1990, 1995, 2000 and 2005 from ‘by-product’ and ‘intentional-use’ sectors are presented in Figure 2. Data presented for emissions from ‘intentional-use’ sectors represent ‘conservative estimates’.



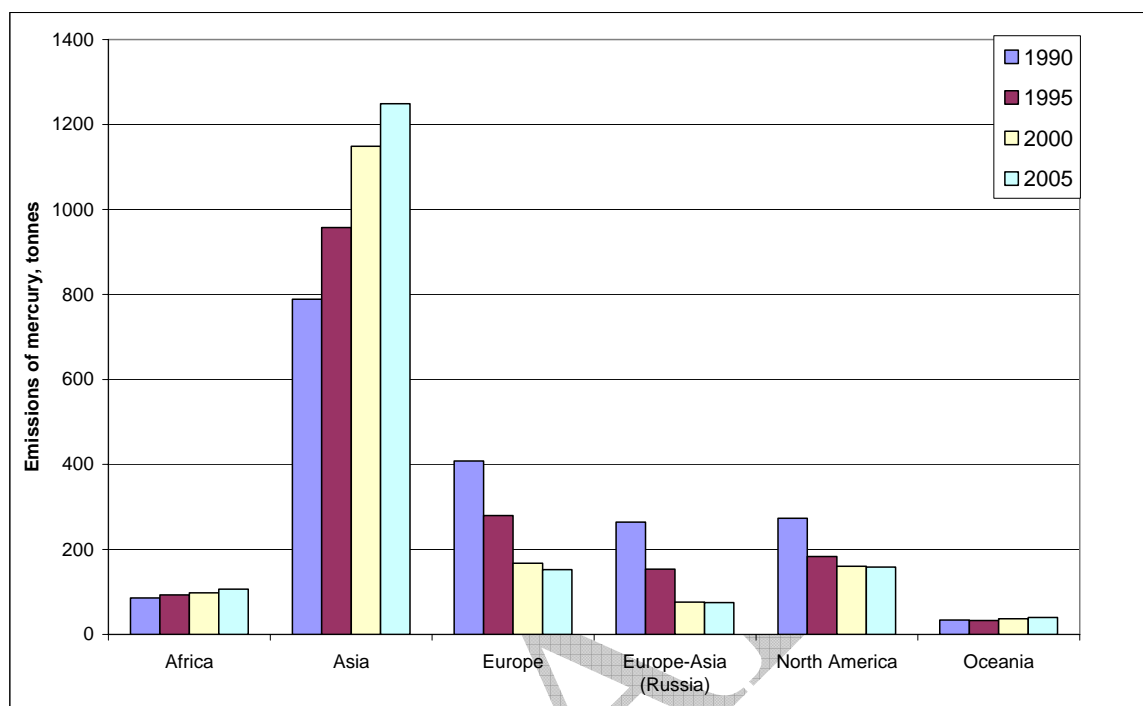
**Figure 2.** Revised estimates of total global anthropogenic mercury emissions to air (tonnes) from ‘by-product’ and ‘intentional-use’ emission sectors in 1990, 1995, 2000 and 2005. (WD = Waste Disposal, , CSP = Caustic Soda Production )

In Figure 2 the left bar for each year shows the revised estimates of by-product emissions for the respective years. The right bar presents the estimated emissions of mercury to air from the intentional use sectors. According to the revised estimates, by-product emissions have increased somewhat from 1990 to 2005, while the intentional use emissions have decreased over the same period of time. Overall, when adding by-product and intentional use sources the level of mercury emissions to air on the global scale has been relatively stable from 1990-2005 and with small variations.

### 2.2.1. Emissions by geographical region

Even though the level of global emissions of mercury to air has been relatively stable since 1990, there has been a considerable regional shift in where the emissions originate. Regional trends in (combined) emissions from ‘by-product’ and ‘intentional-use’ sectors for 1990, 1995, 2000 and 2005 are summarized in Figure 3. The figure shows that anthropogenic mercury

emissions to air have increased substantially in Asia, and to a much lesser extent in Africa and South America while emissions in Europe, Europe-Asia (Russia) and North America have decreased from 1990 to 2005.



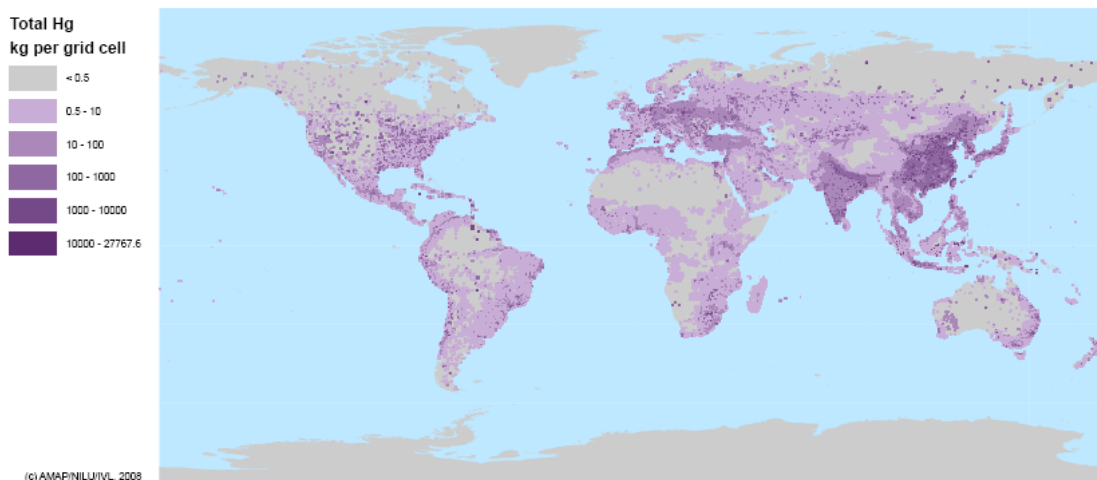
**Figure 3.** Revised estimates of anthropogenic mercury emissions to air (tonnes) in 1990, 1995, 2000 and 2005 from different continents/regions.

In 2005 the Asian countries contributed about 67 percent to the global mercury emissions to air from anthropogenic sources, followed by North America and Europe (UNEP/AMAP 2008). Russia, with its contribution of about 4 percent to global emissions is considered separately due to its territories in both Europe and Asia.

From the compiled inventory data, it is possible to rank individual countries by their emissions. China, with its more than 2000 coal-fired power plants, is the largest single emitter of mercury to air worldwide, by a large margin. Power plant emissions are only a part of the total combustion emissions of mercury in China. Equally significant are emissions from combustion of poor quality coal mixed with various kinds of wastes in small residential units to produce heat and cook food in rural areas.

Together, three countries, China, India, and the United States are responsible for 57 percent of the total estimated global emissions of mercury to air in 2005 (1097 out of 1921 tonnes).

In Figure 4 the global distribution of anthropogenic emissions of mercury in 2005 is shown. The geospatial distribution methodology employed to the emission data is described in UNEP/AMAP, 2008.



**Figure 4.** *Spatially distributed emissions of mercury (from UNEP/AMAP, 2008).*

### **2.3. Scenarios for global mercury emissions to air**

#### ***Purpose of section***

To provide an overview of procedures for deriving scenarios of mercury control and resulting emissions on a global scale.

#### ***Sources of information available for the zero draft text:***

Results from UNEP/AMAP (2008) report on emissions.

#### ***Status of information:***

General scenarios not adapted to selected sector and countries

#### ***Anticipated improvements to be made in the final Paragraph 29 study report***

In Phase 2 of the study, scenarios will be derived based on information received in response to the questionnaires including improved information on status of selected sectors, plans for air pollution control (co-benefits), plans for mercury emission control, etc.

#### **2.3.1. Basic principles**

Scenarios are future projections where emissions of mercury are predicted based on available information on current mercury sources, economical growth, industrial development and implementation of legislation or voluntary agreements to reduce emissions. The latter is linked to availability of relevant control technologies and of course economical factors which may influence the rate of implementation.

In UNEP/AMAP (2008) a set of three scenarios were presented providing the first attempt to project how global mercury emissions from the by product sectors would change until 2020 under different assumptions. A summary of these results are presented here to provide a background to forthcoming work on scenario development in phase 2 of this study.

### **2.3.2. Scenario descriptions**

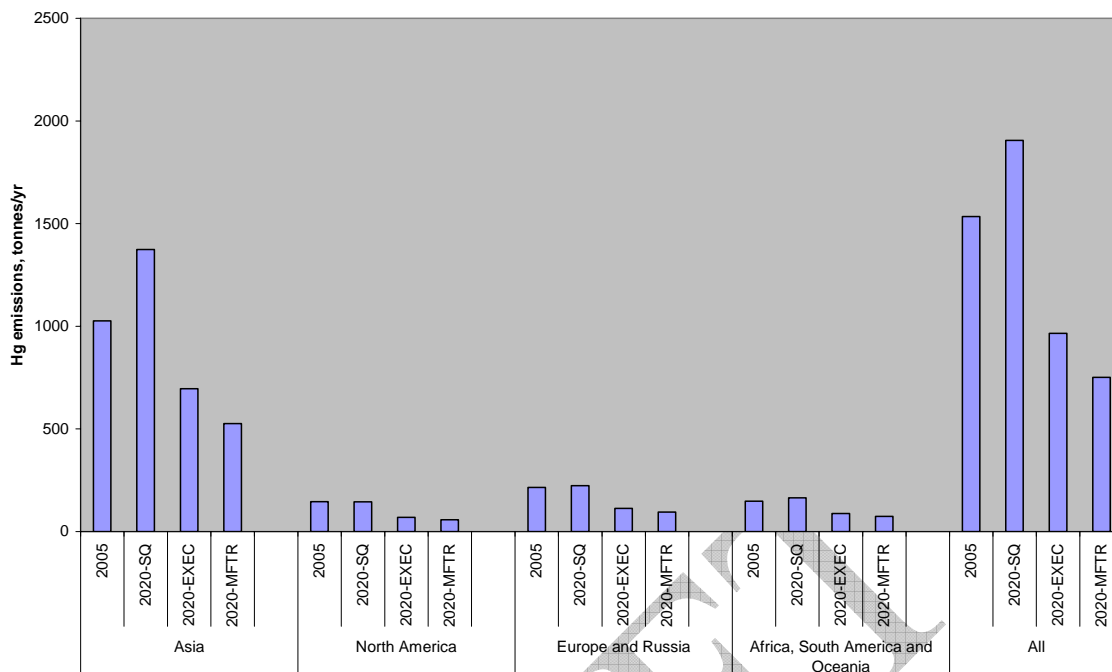
Scenario emissions inventories for the year 2020 were assessed on a global scale in UNEP/AMAP (2008) to investigate the possible implications of actions to reduce mercury emissions. Future mercury emissions are dependent upon a great number of variables, including the development of national and regional economies, development and implementation of technologies for reducing emissions, possible regulatory changes, and also factors connected to global climate change.

As a first attempt to gain insight into the possible implications for global anthropogenic emissions of mercury to the atmosphere, of taking (additional) actions vs. not taking (additional) actions to control emissions, three emissions scenarios were considered for a target year of 2020:

- The 'Status Quo' (SQ) scenario assumes that current patterns, practices and uses that result in mercury emissions to air will continue. Economic activity is assumed to increase, in various regions; e.g. leading to increase in coal consumption in Africa (20%), South America (50%) and Asia (50%), increases in cement production and non ferrous metal production, Emission control practices remain unchanged from those currently employed, leading to increased emissions in several sectors.
- The 'Extended Emissions Control' (EXEC) scenario assumes economic progress at a rate reflecting the future development of industrial technologies. Emissions control technologies; including fabric filters and electrostatic precipitators operated in combination with FGD, activated carbon or impregnated filters currently employed throughout Europe and North America would be implemented elsewhere. It further assumes that emissions control measures adopted under the LRTAP Convention Heavy Metals Protocol, EU Directives, and also agreements to meet IPCC Kyoto targets on reduction of greenhouse gases causing climate change (which will also result in reductions in mercury emissions) will be implemented.
- The 'Maximum Feasible Technological Reduction' (MFTR) scenario assumes implementation of all available solutions/measures, leading to the maximum degree of reduction of mercury emissions and mercury discharges to any environment; cost is taken into account but only as a secondary consideration.

For detailed descriptions of the assumptions made for these scenarios see UNEP/AMAP (2008).

Scenario estimates of by-product sector emissions of mercury to air in 2020 for the three scenarios: SQ, EXEC and MFTR and different regions are presented in Figure 5. The 2005 emission estimates are also presented in this figure for comparison.



**Figure 5.** Comparison of anthropogenic emissions to air (in tonnes per year) of mercury from the 'by-product' sectors in 2005 and under the 2020 SQ, EXEC and MFTR scenarios. Adapted from UNEP/AMAP (2008).

If no major changes in the efficiency of emission control are introduced and economic activity continues to increase (the SQ scenario), global anthropogenic mercury emissions to air are projected to increase by 371 tonnes to a global total of 1906 tonnes (by product emissions only) in 2020. The largest increase in emissions of mercury is projected for stationary combustion, mainly from combustion of coal. For the EXEC scenario, decreases of 569 tonnes are predicted bringing the global total by-product emissions down to 966 tonnes. The difference in predicted by product emissions between the EXEC and SQ scenarios is nearly 1 000 tonnes. In other words, the implementation of available measures and practices (the basic assumption of the EXEC scenario), implies that the annual mercury emissions can be reduced by up to 1000 tonnes in the period to 2020 under the assumptions employed in this scenario discussion. If no measures are taken to improve reduction of mercury emissions the projected emissions in 2020 are more than 100% above those envisaged under the EXEC scenario.

An even greater reduction in mercury emissions to air is projected if the 2020 SQ scenario is compared with the 2020 MFTR emission reduction scenario where by product emissions are predicted to decrease down to 752 tonnes in 2020.

Under the EXEC scenario, clear decreases in mercury emissions to air between 2005 and 2020 are projected for all continents. As might be expected, the largest emissions of mercury in 2020 are estimated for Asia. The 2005 emissions in China of almost 635 tonnes are projected to decrease in 2020 to between 380 tonnes (under the EXEC scenario) and 290 tonnes (under the MFTR scenario). This corresponds to a reduction in Chinese emissions of between 40 and 55%. This decrease assumes that by 2020, all Chinese power plants will be equipped with improved emission control installations. These projections also assume that consumption of coal will increase in China between 2005 and 2020 by a factor of 2 and industrial production by a factor of 1.5. It should be recognized that the projections described for China are based on the

assumption of a rigorous implementation of emission reduction measures, particularly those concerning major improvement in the efficiency of installed emission controls.

For India, similar assumptions as those applied to China were made when scaling emission factors on the basis of projections for improvement of efficiency of emission control installations in Indian power stations and industrial plants by 2020.

The projected decreases in mercury emissions in Europe, North America, Australia, Japan and Russia are between 40 and 60 % when comparing the EXEC scenario with the 2005 emissions.

DRAFT

### 3. Emission control, efficiencies and costs

#### *Purpose of section*

To provide a general overview of available technologies to reduce mercury emissions in the selected sectors and their associated efficiencies and costs, as well as a short general discussion and examples of requirements for cost calculations.

#### *Sources of information available for the zero draft text:*

Results from UNEP qualitative report on costs and efficiencies of emission control (2008), results from EU projects ESPREME, HEIMSTA and various readily available open sources.

#### *Status of information:*

General information not adapted to existing scenarios or specific conditions in the selected countries/sectors.

#### *Anticipated improvements to be made in the final Paragraph 29 study report*

Improved information on technological status of selected sectors in selected countries including current status of control of air pollutants and mercury as well as fuel type and composition based on answers to questionnaires provided by national experts. This information will be used to derive scenarios including mercury emissions to air and associated control costs for different ambition levels.

#### **3.1. Emission control**

For control of mercury emissions in the flue gases after the combustion process a number of different technical approaches can be taken. In many cases, co-control of mercury and other air pollutant emissions is achieved when employing air emission control technologies. For additional control of mercury emissions to air, specific control technologies have been developed often based on addition of sorbets to trap the mercury.

For the selected sectors in this study, many of the potentially applicable co-control and mercury specific control technologies are similar and are thus not presented separately for each sector here. For sector-specific information, see chapters 4.1 to 4.4.

##### **3.1.1. General primary control measures**

Mercury enters combustion or the high temperature industrial process covered in this study as a minor constituent of the fuel, process raw material or waste and a variable fraction of this mercury will be emitted to air after combustion. A primary control measure is thus to reduce the amount of mercury in the fuel, process raw materials or waste before combustion takes place. Another general approach to reduce emissions is to increase the operating efficiency thereby decreasing the amount of fuel or raw materials used and thus the resulting emissions of mercury and other pollutants.

### 3.1.2. Technical co-control of air pollutants and mercury

Modern combustion and industrial processes plants, and many older plants which have been updated, have a range of different emission abatement equipment (Table 2). For several of the abatement technologies the primary target is one type of air pollutant, but the technology may also contribute to removal of other pollutants from the flue gases, e.g. the fabric filter has a secondary function for acid gas control and similarly the wet scrubber for particle control. Often different control systems are needed in combination to achieve a desired control of several pollutants. Generally the abatement equipments installed are those targeted to reduce emissions of pollutants such as particles (PM, particulate matter), sulphur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>), which to a varying degree also may affect mercury emissions. To reach reductions of mercury exceeding the levels already achieved as co-benefit from the more common air pollutant abatement technologies, additional measures to specifically reduce mercury are needed.

**Table 2.** *Some common air pollutant control technologies (Largely from EMEP/EEA air pollutant emission inventory guidebook, 2007).*

Fabric filters (FF)	Consist of semi-permeable material in the form of bags or sleeves which trap particles and which are mounted in an airtight housing (baghouse), which is divided into a number of sections. Fabric filters are also used as a second stage in acid gas control systems (e.g. SO <sub>2</sub> control).
Electrostatic precipitators (ESP)	Use the principle of electrostatic attraction to remove entrained particles from the flue gases. They consist of rows of discharge electrodes (wires or thin metal rods), through which a high voltage is applied, and which run between an array of parallel rows of metal plates which collect the charged particles.
Wet scrubbers	Remove acid gases (e.g. HCl, HF and SO <sub>2</sub> ) by washing the flue gases in a reaction tower designed to provide a high gas-liquid contact. In the first stage the gases are cooled by water sprays, removing HCl, HF, some particulates and some heavy metals. In the second stage calcium hydroxide or another suitable alkali is used to remove SO <sub>2</sub> and any remaining HCl. With lime/limestone wet scrubbing, SO <sub>2</sub> reduction efficiency is > 90 %
Semi-dry scrubbers/ spray absorber systems (spray drying)	Make use of an alkaline reagent slurry (usually calcium hydroxide) which is introduced as a spray of fine droplets. The acid gases (e.g. SO <sub>2</sub> ) are absorbed into the aqueous phase on the surface of these droplets and neutralised to form a dry product, which is collected in an electrostatic precipitator or fabric filter. The SO <sub>2</sub> reduction efficiency is > 90 %.
Dry injection systems	Involve the injection of an alkaline reagent (e.g. calcium hydroxide or sodium bicarbonate) as a fine, dry powder to remove and neutralise acid gases. The neutralised product is normally collected in a fabric filter.
Selective non-catalytic reduction (SNCR) and Selective catalytic reduction (SCR)	Aims at reducing nitrogen oxides (NO <sub>x</sub> ) in the flue gases. The SNCR process involves injection of ammonia or urea near the furnace. A SCR system is based on selective reactions with injected additives in the presence of a catalyst. The additives used are mostly ammonia (gaseous and in solution) but also urea. Emission reduction of NO <sub>x</sub> with SNCR can be limited (up to 50 %) but for SCR between 70 and 90 %.
Adsorption using activated carbon/ activated lignite coke	Several different technologies have been developed for mercury and dioxin control. These systems can also be fairly effective at removing HCl and SO <sub>2</sub> .

Fabric filters (FF) and electrostatic precipitators (ESP) are primarily aimed at reducing particulate matter from the flue gases, but they can also to some extent reduce atmospheric

mercury emissions by removing mercury adsorbed to the particles. The mercury removal efficiency of the filters depends on the filter's capability for removal of small size particles on which mercury may be adsorbed.

Systems designed to remove SO<sub>2</sub> (and other acid gases) from the flue gases, also called flue gas desulphurisation (FGD) systems, are wet scrubbers, semi-dry scrubbers/spray absorber systems and dry injection. All are based on the reaction of SO<sub>2</sub> with an alkaline agent added as solid or as suspension or solution of the agent in water to form the respective salts. Use of FGD processes will also reduce emissions of particulate matter, mercury and other metal emissions.

SNCR and SCR aim at reducing emissions of nitrogen oxides (NO<sub>x</sub>), and have a limited effect on mercury emissions. In e.g. Laudal et al (2002), results indicated that SCR and NH<sub>3</sub> may enhance mercury capture, although it appeared that the impact was highly coal-specific. However, there were significant concerns as to the applicability of the pilot-scale results to full-scale power plants.

Co-control of mercury emissions from combustion sources is mainly determined by the capacity of the installed air pollution control system (filters or scrubbers) to adsorb mercury from the gas phase to solid or liquid phase, which can then be separated from the flowing gas. The adsorption is to a large extent determined by the speciation of the mercury in the stack gases. At combustion temperatures, mercury mainly exists in the form of gaseous elemental mercury (Hg<sup>0</sup>). As the flue gas cools, formation of divalent species such as HgCl<sub>2</sub> can occur. Divalent species are readily absorbed in liquid and solid sorbents and can thus be removed more efficiently from the stack gas. Formation of divalent species is dependent on temperature but also on the composition of the flue gas, which in turn is dependent on the conditions of combustion, composition of the fuel and presence of additives etc. The presence of chloride in coal is one example of an important parameter. Higher concentrations of chloride in coal yields higher concentration of hydrochloric acid in the flue gas and a more efficient oxidation of Hg<sup>0</sup> to divalent form. In any practical case, the speciation of mercury is determined by a number of parameters and can also be highly variable. Since the speciation of mercury affects the possibilities of removal from flue gases via adsorption to liquid or solid sorbents, the efficiency of a specific control technology will be highly variable from one case to another.

Further information on relevant best available techniques (BAT) for the selected sectors can be found in e.g. the work of the European IPCC (Integrated Pollution Prevention and Control) Bureau, please refer to e.g. BREF (Best available technique REFerence) documents at <http://eippcb.jrc.es/reference/>, or US Environmental Protection Agency (USEPA) emission factor handbook (USEPA, AP-42) at <http://www.epa.gov/ttnchie1/ap42/>.

### **3.2. Combining different control technologies for optimised mercury control**

Control of mercury emissions from combustion sources can be achieved by a number of different measures or combination of control measures. Air pollution control technologies (which will reduce mercury emissions to some extent) are described in section 3.1 and examples of available mercury specific controls are described in chapter 4, under the relevant sub sections for each sector. For the development of relevant control strategies for mercury combinations of air pollution control technologies and specific mercury control technologies should be considered. Which air pollution control devices are installed is of course also dependant on other priorities such as reducing emissions of PM or SO<sub>2</sub>. It is thus not possible to present combinations of different control technologies which are generally applicable for optimal mercury emission control without knowledge of the current status of air pollution

control. Other parameters which will affect the selection of potential control options are the technological specification of the emission source and the characteristics of the flue gas (e.g. other components, mercury speciation).

Of the four selected sectors in this study, by far the most information is available on mercury control in coal fired power plants, mainly based on research performed in the USA (see section 4.1). For this sector and under the conditions relevant for the studied power plants in the USA, significant mercury emission reduction can be achieved by the application of activated carbon injection possibly complemented by additional particle removal devices such as fabric filters. The results are based on studies in power plants with existing air pollution control equipment. These results may thus not be directly applicable to other countries where similar air pollution control technologies have not been implemented in the coal fired power plant sector. In the cases where air pollution control is limited or absent, a relevant mercury emission reduction strategy will have to take into account a first step of emission control focussed on air pollutants such as PM, SO<sub>2</sub> and NO<sub>x</sub> (and the achieved co-benefits for mercury) before evaluating the potential benefit of specific mercury control with e.g. activated carbon injection. In addition to this, the efficiency of different control technologies will depend on the composition of the coal, which is also highly variable.

For all four sectors considered in this study, examples of possible combinations of air pollution control and mercury specific control are presented in tables 4, 6, 8 and 10 in chapter 4, based on studies performed in the ESPREME project. These examples are relevant for the current status of the four sectors in Europe but as for the coal combustion case, they may not be directly applicable for other countries.

**In the second phase of this study, information received from the selected countries will form the basis of an evaluation of which control technologies or which combination of control technologies are relevant and feasible for each sector and each country.**

### **3.3. Cost and efficiencies for mercury control**

Estimating costs for control of mercury emissions requires knowledge of the current status of the emission sources including technological descriptions of current and planned air pollution control. The estimated cost of mercury control is highly dependant on the baseline, that is the current (or planned) status of air pollution control. If sufficient general air pollution measures are already installed, any additional mercury specific measures would be calculated and allocated as "cost for mercury control". If no or only insufficient air pollution control technologies are installed, any additional control technology which will capture mercury as a co-benefit can be argued either to be allocated as "cost for mercury control" or not to be allocated to mercury, e.g. depending on the primary objective for the additional control.

In the following sector specific sections, general information on costs of mercury control is presented mainly based on studies in Europe and North America.

Mercury reduction resulting from different combinations of control installations are given in the tables in the following chapters for each of the four sectors covered in this study. In some of the tables a single figure of removal efficiency is given for each control technology combination, as a best general estimate of reduction efficiency. In reality the removal efficiency should rather be seen as an interval since the removal is dependent on a multitude of factors, such as coal quality, combustion conditions etc.

**It is important to note that without information on the current technical status of the sectors, current and planned installations of air pollution control etc. a detailed estimation of the costs of mercury control cannot be made.**

**It is also important to note that to be able to use cost data for scenario development, this data should be given as cost per unit of removed mercury reduction (US\$/kg Hg) or cost per activity (e.g. US\$/MWh<sub>e</sub> for electricity production).**

DRAFT

## 4. Characterisation of the selected sectors

### *Purpose of section*

To provide a brief technical description and information about mercury emissions to air, control measures and associated costs for the selected sectors: coal combustion in power plants and industrial boilers, non-ferrous metal production, cement production and waste incineration.

### *Sources of information available for the zero draft text:*

Results from UNEP qualitative report on costs and efficiencies of emission control (2008) and various readily available open sources.

### *Status of information:*

General descriptions of technologies for coal combustion, cement production, non ferrous metal production and waste incineration. Emissions data are based on the UNEP/AMAP (2008) inventory and updates from literature and on-going AMAP Arctic Mercury Assessment.

### *Anticipated improvements to be made in final Paragraph 29 study report*

Improved information on technological status of selected sectors in selected countries including current status of control of air pollutants and mercury, fuel type and composition and plans for improved emissions control and examples of costs based on answers to questionnaires provided by national experts. This information will be used to derive scenarios including mercury emissions to air and associated control costs for different ambition levels.

### **4.1. Coal combustion in power plants and industrial boilers**

The purpose of coal combustion is to provide heat and electricity for industry and society in general. Combustion of coal can be achieved using several different technologies ranging from stoker boilers to fluidized bed and pulverized coal combustion technologies.

#### **4.1.1. Origin of mercury and emissions from coal combustion**

Mercury is naturally present in coal as a trace contaminant and is released during combustion, entering the atmosphere via the flue gases. Concentrations of mercury in coal vary between geographical regions and are usually in the range 0.1 to 0.3 ppm but higher levels can be also found.

#### **4.1.2. Technologies for coal combustion**

Fluidized bed combustion (FBC) and pulverized coal combustion (PCC) are modern and efficient technologies, usually employed in larger units, which both require pre-treatment of the coal through grinding etc. to achieve suitable size fractions of the coal. Emission control systems on these, usually larger units, are common and economically feasible. Stoker systems have been used in small size boilers for over a century and use a lump coal feed and

combustion. It is relatively inefficient and unstable due to restricted access of oxygen to the combustible material. This leads to intermittent emissions of e.g. CO, NO<sub>x</sub> and VOC. Application of emission control systems to stoker boilers tend to be uneconomic, possibly with the exception of cyclones for particulates removal. (*IEA Clean Coal centre*)

The PCC technology is well developed, and there are thousands of units around the world (*IEA Clean Coal Centre*). PCC can be used to fire a wide variety of coals, although it is not always appropriate for those with high ash content.

FBC have a bed of inert material which is agitated or "fluidised" by preheated air injected through a porous plate or grate from below. The result is a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides effective chemical reactions and heat transfer. The typical relatively low emissions from FBC are achieved by air staging, limestone addition and low combustion temperatures of about 750– 950 °C. FBC is in particular adapted to coals rich in ash. (*EMEP/EEA, 2009, EC 2006*)

Combustion in power plants converts the chemical energy stored in the fuels to either electrical power or heat, or both. Combined heat and power plants are more efficient in utilizing the released energy, whereas in older stoker type power plants, the total energy losses to the environment might be as high as 70 percent of the chemical energy in the fuels, depending on the fuel and the specific technology. In a modern high efficiency power plant, losses are down to about half of the chemical energy contained in the fuels. In a combined heat and power plant a larger fraction of the energy in the fuel is delivered to final users, either as electricity or as heat (for industrial processes or residential heating or similar uses).

#### **4.1.3. Control measures in coal combustion**

A primary control measure is to reduce the amount of mercury in the fuel e.g. by selecting coal with naturally low mercury content, by pre-treatment of the coal or by fuel substitution schemes (e.g., substitution of coal with natural gas or renewable energy sources). Another general approach to reduce emissions is to increase the operating efficiency thereby decreasing the amount of fuel required and thus the resulting emissions of mercury and other pollutants. To control mercury emissions after the combustion step various technical air pollution and mercury specific control measures are possible. Brief summaries of these options are given below.

##### **Pre-treatment of coal**

Apart from the quality and mercury content of the coal also the chemistry of mercury within the coal influences mercury emissions from coal combustion. Coal from different geographical origin may have very different characteristics. The major classes of coal are anthracite, bituminous coal, sub-bituminous coal and lignite where anthracite has the highest carbon content and energy value and lignite the lowest. In an alternative nomenclature system, the coal with the highest carbon content is sometimes named "hard coal" and the lowest "brown coal"<sup>1</sup>.

---

<sup>1</sup> Different systems for classification and nomenclature of coal types are in use internationally, mainly based on the degree of change undergone by a coal as it matures from peat to anthracite – known as coalification. Low rank coals, such as lignite and sub-bituminous coals are typically softer, friable materials with a dull, earthy appearance. They are characterised by high moisture levels and low carbon content, and therefore low energy content. Higher rank coals are generally harder and stronger and often have a black vitreous lustre. They contain more carbon, have lower moisture content, and produce more energy. Anthracite is at the top of the rank scale and has a correspondingly higher carbon and energy content and a lower level of moisture. An alternative nomenclature is "Brown Coal" for the low rank coal and "Hard Coal" or "Black Coal" for the highest rank.

A decrease of mercury emissions from power plants will usually be obtained by the deployment of coal treatment technologies prior to combustion. Coal treatment technologies considered in the context of plant efficiency and mercury removal includes conventional coal washing, coal beneficiation for mercury content, coal blending, and coal additives.

Although coal washing/treatments may produce relatively high reduction rates for mercury with some coals, they are not adequate for use as a reliable method for mercury reduction on all types of coals. The success rate will be site and coal specific (Dronen and others, 2004, in Sloss, 2008). Mercury in coal is associated with reduced sulphur and efficient removal of mercury can be obtained in coal washing optimised for removing sulphur minerals (e.g. pyrite).

Washing with the primary objective to reduce sulphur in bituminous coals also reduces the mercury concentration relative to in-ground concentrations. The removal efficiency varies according to the fraction of mercury in the sulphides in the coal and the efficiency of sulphide removal (Kolker and others, 2006, in Sloss, 2008). Other coal cleaning processes such as froth flotation, selective agglomeration, cyclones and chemical approaches are also aimed at sulphur removal and therefore any mercury reduction is a co-benefit. Mercury reduction in these processes ranges from 10% to as much as 70% with an average of 30% on an energy equivalent basis (Sloss, 2008).

### **Improved operating procedures**

Improvement of plant efficiency (e.g. aiming at lowering production costs) may involve a number of measures designed to conserve fuel (coal) and, as a result, reduce the amount of mercury emissions. Some of the most commonly applicable measures at coal-burning facilities include: new burners, improved air preheater, improved economizer, improved combustion measures, minimization of short cycling, minimization of gas-side heat transfer surface deposits, and minimization of air infiltration. In addition, operation and maintenance (O&M) practices have a significant impact on plant performance, including its efficiency, reliability, and operating cost. A well operated and maintained plant will experience less rapid deterioration of heat rate; hence, O&M practices themselves influence coal use and mercury emissions. Good O&M practices should be an ongoing concern in daily plant operation.

### **Co- control of mercury in coal combustion facilities**

The multi-pollutants control technologies described in chapter 3 are widely used on coal combustion facilities. The reported effectiveness of existing control technologies and co-benefit approaches on mercury capture in coal combustion facilities has been compiled by Sloss (2008) and are summarised in Table 3. The table shows that the ranges of mercury capture for a certain combination of controls may be quite large, and that the degree of capture also depends on the quality of the coal (bituminous coal, sub bituminous coal or lignite). Thus, evaluation of capture of mercury as co-benefit in air pollution control equipment must be made on a plant specific basis and include information on fuel quality, flue gas composition and specific details about the installed air pollution control.

**Table 3.** Example of air pollution controls and their capacity (%) to capture mercury in coal fired power plants, adapted from Sloss (2008). PM=particulate matter, SO<sub>2</sub>= sulphur dioxide, NO<sub>x</sub>= nitrogen oxides.

<b>PM Controls</b>	<b>Bituminous coal</b>	<b>Sub-bituminous coal</b>	<b>Lignite<sup>2</sup></b>
CS-ESP	0-63	0-18	0-2
HS-ESP	0-48	0-27	-
FF	84-93	53-67	-
<b>PM and SO<sub>2</sub> control</b>			
CS-ESP + wet FGD	64-74	0-58	21-56
HS-ESP + wet FGD	6-54	0-42	-
FF + dry scrubber	very high		lower
FF + Wet FGD	62-89		
<b>NO<sub>x</sub>, PM and SO<sub>2</sub> control</b>			
SCR + spray dryer + FF	94-99	0-47	0-96

CS - Cold Side; HS - Hot Side; ESP - Electrostatic precipitators, FF - Fabric filters, FGD - Flue Gas Desulphurisation, SCR - Selective Catalytic Reduction.

Large efforts have been made in the USA to develop technologies for mercury emission control from coal combustion, including extensive full scale tests of the efficiency of control devices for mercury control depending on coal type, type of sorbent and additional additives, temperature and operating conditions. The results of these are summarised in UNEP POG (in prep.) and Sloss (2008).

### **Technical mercury specific control in coal combustion facilities**

In addition to co-benefits from other air pollution control technologies, mercury specific controls can be used.

When designing mercury specific control technologies, these are often based on adsorption of mercury on an added sorbent such as activated carbon, with or without additives to enhance the adsorption capacity. Both elemental and divalent mercury have a high affinity for activated carbon which to some extent removes the dependence of speciation of mercury on control efficiency.

Injection of sorbents into the flue gas of coal-fired boilers for mercury control has been applied at boilers in Germany since the 1990's (Wirling, 2000) and has been demonstrated in the United States on several full-scale systems (GAO, 2009). Sorbents can be added upstream of an existing particulate matter (PM) control device and the mercury is collected in the fly ash fraction. Alternative technologies are where the sorbent is injected after existing PM control devices, in which case an additional particle control unit is needed to capture the mercury

<sup>2</sup> Different systems for classification and nomenclature of coal types are in use internationally, mainly based on the degree of change undergone by a coal as it matures from peat to anthracite – known as coalification. Low rank coals, such as lignite and sub-bituminous coals are typically softer, friable materials with a dull, earthy appearance. They are characterised by high moisture levels and low carbon content, and therefore low energy content. Higher rank coals are generally harder and stronger and often have a black vitreous lustre. They contain more carbon, have lower moisture content, and produce more energy. Anthracite is at the top of the rank scale and has a correspondingly higher carbon and energy content and a lower level of moisture. An alternative nomenclature is “Brown Coal” for the low rank coal and “Hard Coal” or “Black Coal” for the highest rank.

containing sorbent (the toxic emission control process [TOXECON™] configuration). A third demonstrated configuration for sorbent injection is TOXECON II™ in which sorbent is injected into the middle fields of the existing ESP.

Some of the factors that affect the performance of any particular sorbent with regard to mercury capture include (Pavlish et al., 2003 and Srivastava et al., 2006):

- Physical and chemical properties of the sorbent
- Injection rate of the sorbent
- Flue gas parameters such as temperature, concentrations of halogen species (e.g., HCl, HBr), and concentration of sulphur trioxide (SO<sub>3</sub>)
- Existing air pollution control configuration

Large efforts have been made in the USA to develop technologies for mercury emission control including extensive full scale tests of the efficiency of control devices for mercury control depending on coal type, type of sorbent and additional additives, temperature and operating conditions. The results of these are summarised in UNEP POG (In prep.) and Sloss (2008). Most tests were performed with sorbent injection upstream of existing PM controls. Some of the main conclusions are:

- Capture of mercury increases with increasing amount of sorbent added, although an optimal amount was found in some cases where further additions yielded only small effects.
- Lower temperatures (<150 °C) at the ESP inlet favours high mercury capture.
- Efficient control using untreated activated carbon is dependant on the formation of oxidised mercury in the flue gas which is generally favoured at high concentrations of chloride in the coal. A higher efficiency can be achieved with halogen treated carbon, especially in plants using low rank coal with low chlorine contents.

One identified negative aspect of activated carbon injection for mercury control is that the mercury (as well as the added activated carbon) will end up in the fly ashes which reduces the potential for safe disposal or use of the ash in e.g. construction and cement manufacturing. To avoid this, a second particle removal installation can be made and the activated carbon added after the regular particle control device. A technology developed and patented by EPRI (TOXECON™) includes a secondary particle control unit (fabric filter) and has been shown to reduce mercury emissions by over 90%. The majority of the fly ash is thus collected before the mercury control step and has a wider use and marketability. The much smaller ash fraction containing the activated carbon and the mercury is collected in the secondary step.

#### **4.1.4. Costs and efficiencies of control technologies for coal fired power plants**

Coal pre-treatment includes procedures aimed at increasing the performance and energy output in the combustion process or at reducing emissions of harmful substances. Pre-treatment steps include crushing, drying and washing. Addition of chemical reagents or coal blending to achieve better performance is sometimes also made. Coal washing is primarily a measure to reduce ash and sulphur contents of the coal but can also decrease the mercury contents. Direct costs of pre-treatment of coal are thus difficult to allocate specifically to mercury control. Costs for coal blending (i.e. mixing with coal or other fuels with lower mercury content) are dependant on availability and market demand of the blending fuel.

An extensive review of control technologies and the associated costs is available from the IEA Clean Coal Centre (Sloss, 2008).

One important aspect when estimating costs for mercury emission control are the assumptions of baseline conditions. The differences in costs for mercury removal will be very different if the baseline conditions are power plants equipped with modern air pollution control or if very simple emission controls are installed. It is also important to note that to be able to use cost data for scenario development, it should be given as cost per unit of removed mercury reduction (US\$/kg Hg) or cost per activity (US\$/MWh<sub>e</sub> for electricity production).

Reduction of mercury emission from coal combustion is an effect of implementation of technologies for controlling conventional air pollutants (particulate matter, SO<sub>2</sub> and NO<sub>x</sub>) and specific technologies for heavy metal removal. Examples from US power plants reported in the GAO-10-47 (2009) indicate that mercury control can be achieved at most power plants at relatively low costs using carbon injection, but alternative control measures may be needed in other cases. There are also examples where conventional air pollution control installations are sufficient to reach mercury control of >90%. The costs for purchase and installation of injection systems and monitoring equipment are in the range US \$1.2 million to US \$6.2 million per power plant which is quoted as significantly less than conventional air pollution control. For power plants also investing in fabric filters the investment cost was higher – US \$12.7 to US \$24.5 million. The actual amounts of mercury removed are not reported in this study.

In another study, incremental cost of 90% mercury emission control by activated carbon injection was ranged from US\$ 66,000 to US\$ 220,000 per kg of mercury removed (Feeley et al., 2008). The marginal cost for specific removal of Hg from large combustion plants by injection of activated carbon with 80% removal efficiency was estimated by Visschedijk et al. (2006) to be US\$ 225,000/kg Hg removed (150,000 €/kg Hg removed).

For coal combustion, costs of addition of fabric filters to heat and power plants in non-EU countries of UNECE Europe were estimated by Visschedijk et al. (2006) to be US\$ 7 billion annually (4.8 billion €/year). Additional costs of implementation of activated carbon injection in all 44 countries of UNECE Europe (EU and non-EU countries) were estimated to be US\$ 22 billion annually (14.4 billion €/year). Global cost for specific removal of Hg by injection of activated carbon in coal combustion sector was calculated by UNEP (2008) on level US\$ 153 billion annually.

The US EPA has developed a manual for estimating costs of air pollution (including mercury) control in power plants. The method can be used to estimate costs of installation of twelve different technologies for removal of SO<sub>2</sub>, NO<sub>x</sub> and mercury, either as separate components or as an integrated air pollution control system

<http://www.epa.gov/nrmrl/pubs/600r09131/600r09131.html>.

Cost of abatement equipment at Best Available Technique (BAT) level (particulate control + FGD) contributes less than 5 % of the total coal-fired power plant costs (without fuel costs). If the cost of coal is included in the cost of the plant, this contribution is at a level of 3-3.5 %. The basis for the estimation is derived from (Rokke, 2006) for the production cost of a new coal plant of 60 US\$ per MWh, including a fuel cost of 14.10 US\$ per MWh, together with a total cost of BAT technique of 2.28 US\$ per MWh.

Based on an evaluation of control costs performed in the European research project ESPREME, a database of costs and efficiencies for different control options was developed. Annualized costs of selected multi-pollutant reduction technologies per activity and its efficiencies for mercury emission reduction in the coal combustion sector are presented in Table 4 below.

The information in table 4 represents combinations of different control measures which are potentially relevant for Europe and the status of the coal sector in Europe. The same combinations may thus not be relevant elsewhere. Based on the information obtained from the selected countries in this study, an assessment of relevant combinations of control technologies will be made in phase 2.

**Table 4** Cost and efficiencies of installations used to reduce Hg emissions from coal combustion processes (in US\$/MWh<sub>e</sub>) – selected technologies from the EU ESPREME project database (<http://espreme.ier.uni-stuttgart.de>).

Sector	Emission control technology	Hg reduction (%)	Annual costs (US\$ 2008/MWh <sub>e</sub> )		
			Annual investment costs	Annual operating costs	Annual total costs
Hard and brown coal combustion <sup>3</sup>	fuel cleaning/ washing – medium emission control efficiency	25	0.00	0.05	0.05
	dry electrostatic precipitator (ESP) – medium	24	0.45	0.90	1.35
	fabric filters (FF) – medium emission control efficiency	20	0.46	1.47	1.93
	dry ESP – retrofitted from medium to high control efficiency	32	0.92	0.52	1.44
	fuel washing +ESP or FF – medium	60	0.46	1.02	1.48
	coal thermal pre-treatment – emerging method	70	1.38		
	FF+wet or dry FGD scrubbers+sorbent injection – state-of-the-art (BAT)	98	0.72	1.80	2.52
	dry ESP + wet or dry FGD scrubber + dry injection – state-of-the-art	98	2.73	2.40	5.13
	electro-catalytic oxidation – emerging method	80	8.55	11.76	20.31
	integrated gasification combined cycle (IGCC) – emerging method	90			20.00

In the table a single figure of removal efficiency is given for each control technology combination, as a best general estimate of reduction efficiency, for use in the calculations. In reality, as has also been presented earlier in this report (chapter 3), the removal efficiency

<sup>3</sup> Different systems for classification and nomenclature of coal types are in use internationally, mainly based on the degree of change undergone by a coal as it matures from peat to anthracite – known as coalification. Low rank coals, such as lignite and sub-bituminous coals are typically softer, friable materials with a dull, earthy appearance. They are characterised by high moisture levels and low carbon content, and therefore a low energy content. Higher rank coals are generally harder and stronger and often have a black vitreous lustre. They contain more carbon, have lower moisture content, and produce more energy. Anthracite is at the top of the rank scale and has a correspondingly higher carbon and energy content and a lower level of moisture. An alternative nomenclature is “Brown Coal” for the low rank coal and “Hard Coal” or “Black Coal” for the highest rank.

should rather be seen as an interval since the removal is dependent on a multitude of factors, such as coal quality, combustion conditions etc.

In a study focussed on evaluating the effectiveness of the UN ECE Heavy Metals protocol and additional measures, Visschedijk et al. (2006) derived average costs of emission control which are presented in Table 5. The assumed baseline conditions was an initial package of particle emission control for preventing dust emissions followed by a specific mercury removal step using activated carbon injection.

**Table 5.** Investment and operational costs of control techniques for energy sector

	<b>Total investment costs</b> (US\$ per GJ of annual used fuel)	<b>Annual operational costs</b> (US\$/GJ fuel)
coal-fired power plants - advanced PM emission control)	4.20	0.80
coal-fired power plants - removing Hg from the flue gases	5.00	1.10
oil-fired power plants - ESP retrofit	0.39	0.04

#### **4.2. Non ferrous metal production**

Non-ferrous metal production includes the production of e.g. zinc, copper, lead and gold. The non-ferrous metals are produced from mined ores which are treated in several process steps to extract the final product.

##### **4.2.1. Origin of mercury and emissions from non-ferrous metal production**

Mercury emissions from non-ferrous metal production depend mainly on the content of mercury in the non-ferrous metal ores used and the type of industrial technology, as well as the control technology employed in the production of non-ferrous metals. Mercury occurs as an impurity in many sulphide ores because it can substitute the elements zinc, copper, cadmium, bismuth, lead, and arsenic. In some metal ores it also occurs as elemental mercury or as an alloy with other metals (amalgams). In some of these deposits mercury contents were high enough to allow an aimed production of mercury as a by-product. A global average of 123 mg mercury/kg in zinc ore resulting in a mobilization of 600 t mercury during zinc production has been estimated. Most of the mercury associated with copper is found in massive sulphide deposits. The mercury fraction is a function of the zinc concentration and the environmental conditions during formation of the deposit. Mercury is commonly found associated with gold deposits although the amount of mercury in gold ore can vary widely, from less than 0.1 mg/kg to over 100 mg/kg (Hagemann et al, 2010 and references therein)

Mercury content in extracted ore is in the UNEP toolkit reported to be between 2.1 and 25 g/metric ton ore, depending on the geographical location.

The industrial technology employed will to a large extent determine the fate of the mercury contained in the ore. If high temperature processes (i.e. roasting and sintering) are used in the initial treatment of the ore, the mercury will be released to air whereas if electrolytic processes are employed, the mercury will remain in the liquid phase (Figure 6).

In the high temperature process, during the roasting and sintering processes, most of the mercury in the concentrate is expected to be evaporated from the oxidation. The evaporated mercury follows the gas stream which can be cleaned by particle filters (cyclones) and dry and wet electrostatic precipitators (ESPs), or scrubbers, resulting in either dry solid wastes or sludges containing mercury (UNEP toolkit). Remaining mercury from roasting or sintering is expected to follow the residue to recycling or deposition.

The leaching process as a part of the electrolytic process, results in a mercury containing liquid leach product and a solid residue. Parts of remaining mercury may follow precipitates to further processing from the purification process. No data has been identified on mercury emissions from the electrolysis step (UNEP Toolkit).

The smelting process can include secondary materials which in principle could represent a source of mercury. Mercury in a smelter feed will be volatilized and enter the gas stream.

Mercury emissions from fuels used in heating processes are regarded to be less significant.

The main steps for non-ferrous metals production and the mercury flows within the steps can be observed in Figure 6.

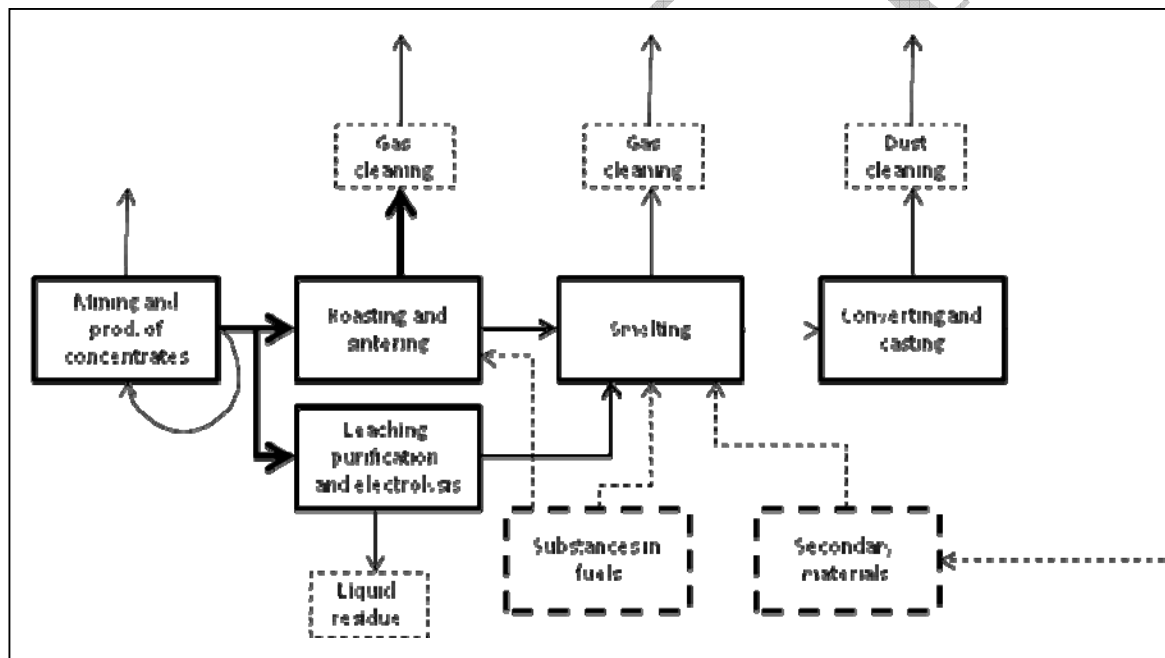


Figure 6. Main steps for non-ferrous metals production and the mercury flows within the steps. Roasting/sintering and Smelting are the high temperature processes where mercury may primarily be emitted to air.

#### 4.2.2. Technologies for non-ferrous metal production

There are many technologies that are used for production of non-ferrous metals. Distinction can be made between the more widely used hydrometallurgical (electrolysis) process, and the pyrometallurgical (thermal) processes.

The pyro-metallurgical process treats minerals and metallurgical ores and concentrates thermally to extract the metal, thus most pyro-metallurgical processes require energy input to

sustain the temperature at which the process takes place. The energy is usually provided in the form of fossil fuel combustion.

In the hydrometallurgical process, chemistry is used for the recovery of metals from ores, concentrates, and recycled or residual materials.

Different technologies and combinations of technologies can be employed in the steps shown in Figure 6.

#### **4.2.3. Control measures in non-ferrous metal production**

Non ferrous metal ores (e.g. copper, zinc, pyrite and lead) often contain mercury as a trace contaminant. General technical air pollutant control technologies described in chapter 3 are used on non-ferrous metal production facilities. The air pollution controls can also, to a varying degree, capture mercury in the flue gases (see Table 3). In addition to co-benefits from common air pollution control technologies, mercury specific controls can be used.

Development of mercury control technologies for non-ferrous metal production facilities has been driven both by ambitions to reduce air emissions but also to prevent mercury from contaminating the sulphuric acid which is produced after the roasting of the sulphur-containing minerals. Some mercury will be removed from the flue gas via precipitation (in e.g. scrubber or filter units for air pollution control) with selenium or sulphate already present in the ores.

Several different methods are available for specific removal of mercury from the flue gases. Processes where mercury is converted to a solid chemical compound which can be removed via precipitation, scrubbing or filtering include the Outokumpu and Bolkem processes where the mercury is precipitated as solid sulphate compounds and the Boliden Norzink process where mercury is precipitated in the form of mercurous chloride. Alternative methods include carbon or selenium filters (for low concentration treatment) or selenium scrubbers. Additional information is available on [http://www.sulphuric-acid.com/techmanual/GasCleaning/gcl\\_hg.htm#Boliden%20Norzink%20Process](http://www.sulphuric-acid.com/techmanual/GasCleaning/gcl_hg.htm#Boliden%20Norzink%20Process)).

#### **4.2.4. Costs and efficiencies of control technologies for non ferrous metal production.**

Large non-ferrous smelters use high efficiency air pollution control devices to control particle and SO<sub>2</sub> emissions from roasters, smelting furnaces, and convertors. Mercury is emitted mostly in a gaseous form and therefore, the ESPs are not very effective in the element removal. Control of flue gas emissions is achieved by absorption of sulphur dioxide in the sulphuric acid plants, which are commonly a part of the smelting plants. Combination of dry ESP, wet scrubbers, mercury removal and wet ESP is considered as BAT in the EU (EC, 2001a). The amount of remaining emissions depends on the content of mercury in the ore.

One important aspect when estimating costs for mercury emission control are the assumptions of baseline conditions. The differences in costs for mercury removal will be very different if the baseline conditions are production plants equipped with modern air pollution control or if very simple emission controls are installed. It is also important to note that to be able to use cost data for scenario development, it should be given as cost per unit of removed mercury (US\$/kg Hg) or cost per activity (e.g. US\$/tonne produced metal).

General cost for industrial combustion of solid fuels (specific removal of Hg by injection of activated carbon, 80% removal efficiency) was estimated by Visschedijk et al. (2006) on the level of US\$ 250,000/kg Hg removed (168,000 €/kg Hg removed). For existing non-ferrous

metal smelters, costs of retrofitting fabric filters were estimated by Visschedijk et al. (2006) to be on the level of US\$ 243 million annually (162 million €/year) in EU-25 and US\$ 374 million annually (249 million €/year) in non-EU countries of UNECE Europe, in sum US\$ 620 million annually.

Annualized costs of selected multi-pollutant reduction technologies per production of 1 tonne of metal production, indicated as specific activity indicator, and its efficiencies for mercury emission reduction are presented in Table 6 below, based on the results of the ESPREME project (<http://espreme.ier.uni-stuttgart.de>).

**The information in Table 6 represents combinations of different control measures which are potentially relevant for Europe and the status of the non ferrous metal production sector in Europe. The same combinations may thus not be relevant elsewhere. Based on the information obtained from the selected countries in this study, an assessment of relevant combinations of control technologies will be made in phase 2.**

*Table 6. Cost and efficiencies of installations used to reduce Hg emissions from non-ferrous metal production (in US\$/tonne of specific production - SAI) – selected technologies from the EU ESPREME project database (<http://espreme.ier.uni-stuttgart.de>).*

Sector	Specific activity indicator (SAI)	Emission control technology	Hg reduction (%)	Annual costs (US\$ 2008/SAI)		
				Annual investment costs	Annual operating costs	Annual total costs
Primary lead	tonne primary lead	dry ESP – medium efficiency of emission control	5	0.06	0.04	0.10
		fabric filters (FF) – state-of-the-art	10	0.12	1.12	1.24
		virgin activated carbon injection (SIC)+FF+FGD – optimized	90	2.48	1.32	3.80
Primary zinc	tonne primary zinc	dry ESP – medium	5	0.10	0.06	0.16
		fabric filters – state-of-the-art	10	0.39	0.75	1.14
		virgin activated carbon injection (SIC)+FF+FGD - optimized	90	2.48	1.32	3.80
Primary copper	tonne primary copper	fabric filters – medium	5	1.80	13.80	15.60
		fabric filters – state-of-the-art	10	3.87	25.65	29.52
Secondary lead	tonne secondary lead	dry ESP – medium	5	0.10	0.06	0.16
		fabric filters – state-of-the-art	10	6.75	1.12	7.87
Secondary zinc	tonne secondary zinc	dry ESP – state-of-the-art	5	0.10	0.06	0.16
		fabric filters – state-of-the-art	10	0.12	1.42	1.54
		virgin activated carbon injection (SIC)+FF+FGD - optimized	90	1.80	1.42	3.32
Secondary copper	tonne secondary copper	dry ESP – state-of-the-art	5	10.89	15.86	26.75
		fabric filters – state-of-the-art	10	6.64	43.97	50.61

In the table a single figure of removal efficiency is given for each control technology combination, as a best general estimate of reduction efficiency, for use in the ESPREME

calculations. In reality, as has also been presented earlier in this report, the removal efficiency should rather be seen as an interval since the removal is dependent on a multitude of factors.

In a study focussed on evaluating the effectiveness of the UN ECE Heavy Metals protocol and additional measures, Visschedijk et al. (2006) derived average costs of emission control in non-ferrous metal smelters which are presented in Table 7. The assumed baseline conditions was an initial package of particle emission control for preventing dust emissions followed by a specific mercury removal step using activated carbon injection.

**Table 7.** Investment and operational costs of control techniques for non-ferrous metal production.

	<b>Total investment costs</b> (US\$ per tonne annual production capacity)	<b>Annual operational costs</b> (US\$/tonne metal)
primary lead production (additional high performance fabric filters)	250	24
primary zinc production	248	26
primary copper production	375	38

### **4.3. Cement production**

#### **4.3.1. Origin of mercury and emissions from cement production**

Concentrations of mercury are naturally present in raw materials (e.g. limestone) used for cement production, and also in fuels used in the process, leading to mercury entering the cement kiln system.

Natural raw materials for cement production like limestone, chalk marl, shale or clay are extracted from quarrying and mining operations (e.g. rock drilling, blasting, excavation, hauling and crushing), before they are crushed in a mill or press and made chemically homogeneous by mixing the raw materials in controlled proportions.

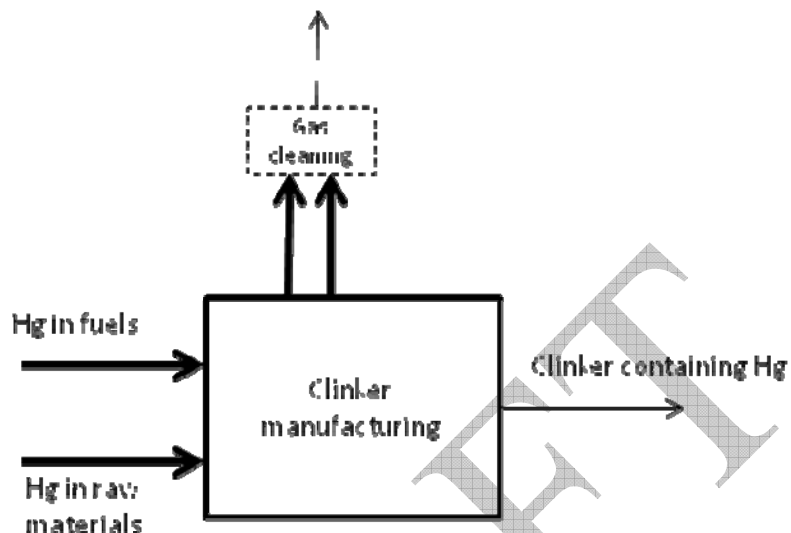
The raw output (dry powder or slurry) from the extraction and preparation process is fed into the kiln and treated thermally to produce clinker. The thermal treatment involves 1) drying and preheating, 2) calcinations and 3) sintering. After being cooled, the clinker is milled together with gypsum ( $\text{CaSO}_4$ ) to make cement and subsequently stored in silos.

Because of its properties, power station ash (fly ash or bottom ash), blast furnace slag, or other process residues (iron slag, paper sludge, silica fume, pyrite ash, and phoshogypsum) can be mixed into the cement. The fly ash used may contain mercury but it is difficult to assess how much of mercury enters the environment through this pathway.

Regardless of the types of processes and kiln type (e.g. wet- and dry-kiln processes), mercury is introduced into the kiln with raw materials, where the mercury content varies from region to region, and with fuels of varying mercury content. The main output of mercury in the clinker manufacturing process is expected to occur in the kiln where mercury leaves the kiln with the dust and exhaust gas (Figure 7). The drying process is expected to produce low mercury emissions to air since the drying temperature is usually well below the boiling point of

mercury. This however might not be the case for every dryer since some are operated at high temperatures leading to mercury being volatilized to a higher extent (UNEP toolkit).

Mercury that is not emitted to air or captured in emission control equipment can remain in the cement product. According to the UNEP toolkit the content is expected to be between 0.02 – 0.1 g mercury per ton of cement (UNEP toolkit).



**Figure 7.** Mercury flows in the clinker manufacturing process.

Since cement production includes energy intensive processes, fuel use consists of a large part of the production costs. Various fuels are used to generate the heat required for the clinker manufacturing process, mainly pulverized coal (black coal and lignite) and petcoke, heavy fuel oil and natural gas, but also other, less expensive fuels, such as shredded municipal garbage, chipped rubber, petroleum coke, and waste solvents are widely used and may contribute to mercury emission from cement production (Pacyna et al., 2009). According to the IPPC (Integrated Pollution Prevention and Control) document on BAT (Best Available Techniques) in the cement manufacturing industries (IPPC, 2006), fuel consumption in the European cement industry is dominated by petcoke (39%), and coal (36%), but they are also using fuel oil (7%), lignite (6%), gas (2%), as well as different types of waste (10%).

An EPA study (EPA, 2009) prepared for the proposed rule on national emission standards for hazardous air pollutants from the Portland cement manufacturing industry, showed that for about 55 percent of the kilns, non-limestone mercury accounted for greater than 50 percent of the kiln's mercury emissions (i.e. origins from other raw materials or from fuels). It should be noted, however, that the studied origins of mercury was varying a lot between the investigated kilns.

#### **4.3.2. Control measures in cement production**

Primary measures to reduce mercury emissions in cement production are careful selection and control of substances entering the kiln (EC, 2001b). Selection of raw materials and fuels with low contents of sulphur, nitrogen, chlorine, metals and volatile organic compounds is necessary. Another primary measure is to ensure efficient operation of the plant.

The major air pollution problem from cement production is dust emissions. The best available techniques for reducing dust emissions are the combination of primary measures, removal of dust from point sources and prevention of dust emissions from fugitive sources. Removal of dust from point sources can be obtained by electrostatic precipitators (ESPs) with fast measuring and control equipment or fabric filters (FFs) with multiple compartments and "burst bag" detectors. Fugitive dust abatement consist of open pile wind protection, water spray injection systems, paving road wetting, vacuum cleaning, closed ventilation systems and closed storage of raw materials (Panasiuk et al., 2006).

Emissions of mercury to air from cement production depend on the use of abatement technology such as fabric filters or ESPs but information on removal efficiencies of mercury specifically from cement kilns is scarce. It can, in general, be expected that mercury removal efficiencies in kilns are comparable to mercury removal efficiencies with similar devices employed in e.g. power plants. One way of minimizing mercury emissions is to lower the exhaust temperature, which leads to less volatilisation and a higher share of the mercury bound to particles which can be trapped in particle control equipment.

#### **4.3.3. Costs and efficiencies of control technologies for cement production.**

One important aspect when estimating costs for mercury emission control are the assumptions of baseline conditions. The differences in costs for mercury removal will be very different if the baseline conditions are cement plants equipped with modern air pollution control or if very simple emission controls are installed. It is also important to note that to be able to use cost data for scenario development, it should be given as cost per unit of removed mercury (US\$/kg Hg) or cost per activity (US\$/tonne cement).

Cost for Hg reduction for cement production (specific removal of Hg from cement oven by injection of activated carbon) was estimated by Visschedijk et al. (2006) to be around US\$ 210,000/kg Hg removed (144,000 €/kg Hg removed). For cement production, costs of application of high performance ESP and FF to control primary emission from cement kilns (i.e. implementation of EU IPPC Directive) in non-EU countries of UNECE Europe were estimated to be US\$ 230 million annually (156 million €/year). Additional costs of injection of activated carbon were estimated on level US\$ 4 billion annually (2,6 billion €/year) for all UNECE countries (Visschedijk et al. 2006).

Annualized costs of selected multi-pollutant reduction technologies per production of 1 tonne of cement and its efficiencies for mercury emission reduction are presented in Table 8 below.

**The information in Table 8 represents combinations of different control measures which are potentially relevant for Europe and the status of the cement production sector in Europe. The same combinations may thus not be relevant elsewhere. Based on the information obtained from the selected countries in this study, an assessment of relevant combinations of control technologies will be made in phase 2.**

Table 8. Cost and efficiencies of installations used to reduce Hg emissions from cement production (in US\$/tonne of cement) – selected technologies from the EU ESPREME project database (<http://espreme.ier.uni-stuttgart.de>).

Sector	Emission control technology	Hg reduction (%)	Annual costs (US\$ 2008/tonne cement)		
			Annual investment costs	Annual operating costs	Annual total costs
Cement production	dry ESP – medium efficiency of emission control	5	0.20	0.15	0.35
	fabric filters – medium	5	0.20	0.22	0.42
	dry ESP – optimized	70	0.42	0.22	0.64
	fabric filters – optimized	70	0.39	0.37	0.76
	fabric filters+wet FGD – optimized	90	1.35	0.45	1.80

In the table a single figure of removal efficiency is given for each control technology combination, as a best general estimate of reduction efficiency, for use in the calculations. In reality, as has also been presented earlier in this report, the removal efficiency should rather be seen as an interval since the removal is dependent on a multitude of factors.

In a study prepared as a basis for discussions of additional measures to control heavy metals emissions within the UN ECE CLRTAP, average costs of emission control techniques for cement production (fabric filters) were estimated by Visschedijk et al. (2006):

- total investment costs: 6.80 US\$ per tonne annual production capacity,
- annual operational costs: 0.60 US\$/tonne cement.

#### **4.4. Waste incineration**

##### **4.4.1. Origin of mercury and emissions from waste incineration**

The main influences on the total emission of mercury to air from waste incineration is the mercury content in the waste, the waste burning capacity of the incinerator, the type of incinerator (mass burn excess air or modular starved air), the way in which it is operated (e.g. whether it includes heat recovery) and the degree of abatement fitted to the plant. Pre-treatment of the waste such as separating and removing mercury-containing material before the waste is introduced into the incinerator is the most important primary measure to reduce mercury emissions to air.

Mercury can be present in household waste in highly variable concentrations in different countries, mainly depending on the occurrence of mercury in household products and the existence of systems for collection of mercury or if the products are disposed on in the regular waste stream. Common product groups which may contain mercury are batteries, thermometers and fluorescent light sources.

#### **4.4.2. Technologies for municipal solid waste incineration**

There are many different furnace designs and combustion techniques in use for municipal solid waste (MSW) incineration. In a typical incinerator, refuse is fed into the combustion chamber and placed on a grate that moves the waste through the combustor, mixing the waste thoroughly with the hot air to ensure effective combustion. Many incinerator designs have two combustion chambers. Air is supplied to the primary chamber through the waste (primary air). The incomplete combustion products (CO and organic compounds) pass into the secondary combustion chamber where additional air (secondary air) is added and combustion is completed.

There are three key classes of MSW incineration technology which depend on the quantity and form of the waste burned. These are mass burn units, modular combustors and fluidised bed combustors (EMEP/EEA, 2009). In mass burn units, the MSW is incinerated without any pre-processing other than the removal of items too large to go through the feed system and removal of hazardous items, e.g. compressed gas cylinders. Modular combustors are similar to mass burn combustors as they burn waste that has not been pre-processed, but they are generally smaller, ranging in size from 4 to 130 tonnes waste/day. One of the most common types of modular combustors is the starved air or controlled air type. They are used where start-ups occur each day and/or where throughputs are low, for example at commercial or factory sites in rural areas. Fluidised bed combustors are widely applied to the incineration of finely divided wastes. For the combustion of MSW in fluidized bed combustion (FBC), the waste has to be treated (e.g. shredded) in order to obtain a suitable size. The fluidised bed incinerator is a lined combustion chamber in the form of a vertical cylinder. In the lower section, a bed of inert material, (e.g., sand or ash) on a grate or distribution plate is fluidised with air. The waste for incineration is continuously fed into the fluidised sand bed from the top or side (EC, 2006a). Preheated air is introduced into the combustion chamber via openings in the bed-plate, forming an agitated or "fluidised" bed. Because of the well-mixed nature of the reactor, fluidised bed incineration systems generally have a uniform distribution of temperatures and oxygen, which results in stable operation (EC, 2006a)

Hazardous waste, which may have high mercury content, is usually burned either in special technology incinerators or in rotary kiln type furnaces. Special technology incinerators include very low technology drum type, grate type, or muffle type furnaces. Also, other technologies (such as supercritical water oxidation, and electric arc vitrification) which treat hazardous waste, can be included in this group (although they are not necessarily classified as "incineration"). Hazardous waste is in some countries incinerated at cement plants and light weight aggregate kilns. In some countries medical waste is incinerated in hazardous waste incinerators or in municipal waste incinerators suited for the purpose (UNEP, 2005).

#### **4.4.3. Control measures in waste incineration**

Since all mercury emitted to air from waste incineration originates from mercury in the waste, the most important primary measure is to reduce the input of mercury to the incinerator. This can be accomplished by sorting out mercury containing products from the waste stream prior to incineration.

In waste incineration, the removal efficiency of the controls may be enhanced by adsorbing the mercury vapours from the combustion chamber onto acid gas adsorbent material or other adsorbents and then removing the particle-phase mercury. The PM control devices most frequently used in the USA are electrostatic precipitators (ESPs). To achieve high mercury control, reducing flue gas temperature at the inlet to the control device to 175 °C (or lower) is

beneficial. Typically, newer municipal waste combustion systems use a combination of gas cooling and duct sorbent injection (DSI) or spray dryer (SD) systems upstream of the particle removal device to reduce temperatures and provide a mechanism for acid gas control.

Under incineration conditions at temperatures above 850°C and O<sub>2</sub> content of 8-10% vol, the prevailing mercury species will be mercury chlorides (I and II) and elemental mercury (Velzen et al. 2002). The thermodynamically calculated chemical equilibrium for mercury in a typical flue gas containing HCl and SO<sub>2</sub> shows that the major product between 300 and 700°C is HgCl<sub>2</sub>, whereas above 700°C elemental mercury is the dominant species. A summary of mercury removal efficiencies for different flue gas cleaning equipment in incinerators is shown in Table 9 (Velzen et al., 2002). For the estimation it is assumed that the HgCl<sub>2</sub>/Hg(0) ratio is between 70/30 and 80/20. 'Special absorbents' (or adsorbents) added may be absorbents impregnated with sulphur or sulphur compounds or active carbon based adsorbents, which increase the sorption of mercury on particles.

**Table 9.** Mercury removal efficiencies of flue gas cleaning systems for waste incinerators (UNEP toolkit)

Equipment	Temp. (°C)	HgCl <sub>2</sub>	Hg(0)	Overall**	Reference
Electrostatic precipitator (ESP)	180	0-10%	0-4%	0-8%	Velzen et al 2002
Electrostatic precipitator (ESP)				10%	Pirrone et al 2001
Fabric filters (FF)				29%	Pirrone et al 2001
Wet scrubbers	65-70	70-80%	0-10%	55-65%	Velzen et al 2002
Wet scrubbers with conditioning agent		90-95%	20-30%	76-82%	Velzen et al 2002
Spray absorbers+ FF (limestone)	130	50-60%	30-35%	44-52%	Velzen et al 2002
Spray absorbers+ FF (special absorbents added)*		90-95%	80-90%	87-94%	Velzen et al 2002
Entrained flow absorbers + FF (special absorbents added)*	130	90-95%	80-90%	87-94%	Velzen et al 2002
Circulating fluidized bed + FF (special absorbents added)*	130	90-99%	80-95%	87-98%	Velzen et al 2002
ESP or FF + carbon filter beads				99%	Pirrone et al 2001
ESP or FF + carbon injection				50->90%	Pirrone et al 2001
ESP or FF + polishing wet scrubber				85%	Pirrone et al 2001

\* Special absorbents may be absorbents impregnated with sulphur or sulphur compounds or active carbon based absorbents, which increase the sorption of mercury on particles.

As shown in the table, simple electrostatic precipitators sometimes only have very low mercury removal efficiencies. Wet scrubbers or spray absorbers using limestone for acid gas removal has efficiencies of 55-65% and 44-52%, respectively. For obtaining high removal efficiency, more than 90%, the addition of special absorbents/adsorbents, most often activated carbon, is a requisite.

#### 4.4.4. Costs and efficiencies of control technologies for waste incineration.

For mercury removal adsorption using carbon based reagents is generally required to achieve BAT level of emission (EC, 2006). The precise abatement performance depends on the levels

and distribution of mercury in the waste. Some waste streams have very highly variable mercury content so additional waste pre-treatment is required.

One important aspect when estimating costs for mercury emission control are the assumptions of baseline conditions. The differences in costs for mercury removal will be very different if the baseline conditions are plants equipped with modern air pollution control or if very simple emission controls are installed. It is also important to note that to be able to use cost data for scenario development, it should be given as cost per unit of removed mercury reduction (US\$/kg Hg) or cost per activity (US\$/tonne of waste).

Based on work performed in the EU funded project ESPREME, annualized costs of selected multi-pollutant reduction technologies per 1 tonne of municipal wastes and its efficiencies for mercury emission reduction were derived and are presented in Table 10 below.

**The information in Table 10 represents combinations of different control measures which are potentially relevant for Europe and the status of the waste incineration sector in Europe. The same combinations may thus not be relevant elsewhere. Based on the information obtained from the selected countries in this study, an assessment of relevant combinations of control technologies will be made in phase 2.**

DRAFT

Table 10. Cost and efficiencies of installations used to reduce Hg emissions from waste incineration (in US\$ /tonne of wastes) – selected technologies from the EU ESPREME project database (<http://espreme.ier.uni-stuttgart.de>).

Sector	Emission control technology	Hg reduction (%)	Annual costs (US\$ 2008/ tonne waste)		
			Annual investment costs	Annual operating costs	Annual total costs
Waste incineration and cremation processes	heat recovery – state-of-the art	5	0.03	0.00	0.03
	cyclones - medium efficiency of emission control	0	0.08	0.04	0.12
	dry ESP – medium	5	0.12	0.06	0.18
	fabric filters – medium	5	0.12	0.06	0.18
	wet scrubber (wSC)– medium	20	0.12	0.08	0.20
	waste separation – medium	60	0.60	0.60	1.20
	dry ESP – optimized	70	1.84	6.99	8.83
	virgin activated carbon injection (SIC)+FF – optimized	80	2.19	4.02	6.21
	two-stage scrubber+wet ESP – optimized	90	2.31	1.82	4.13
	ESP+wet scrubber+activated carbon with lime+FF – optimized	99	2.31	2.48	4.79
	virgin activated carbon injection (SIC)+venturi scrubber+ESP – optimized	95	5.25	6.15	11.40
	virgin activated carbon injection (SIC)+venturi scrubber with lime milk+caustic soda+FF– optimized	99	5.78	7.08	12.86

In the table a single figure of removal efficiency is given for each control technology combination, as a best general estimate of reduction efficiency, for use in the calculations. In reality, as has also been presented earlier in this report, the removal efficiency should rather be seen as an interval since the removal is dependent on a multitude of factors.

Average costs of emission control techniques for medical waste incineration (pre-dedusting with an ESP, followed by lime and activated carbon injection and finally a fabric filter) were estimated by Visschedijk et al. (2006):

- total investment costs: 22.50 US\$ per tonne annual incinerated waste,
- annual operational costs: 2.25 US\$/tonne waste.

Since the costs related to appropriate incineration and land filling are high and medium respectively, in developed countries, these settings are economically hard to manage in least

developed countries. Based on these high costs, opportunities to substitute mercury-free alternatives may be the most preferable option (UNEP, 2008).

DRAFT

## **5. Summary and plans for second phase of study**

### **5.1. Summary**

The purpose of this report is to provide a background overview of mercury emissions to air, control options in selected sectors and their efficiencies and costs. Scenarios for future mercury emissions are also presented here, derived as a part of a previous emission inventory study performed by UNEP/AMAP (2008). These scenarios were developed from general statistical information on growth of economies and energy demand in combination with a set of assumed measures related to air pollution control, energy savings and specific mercury control

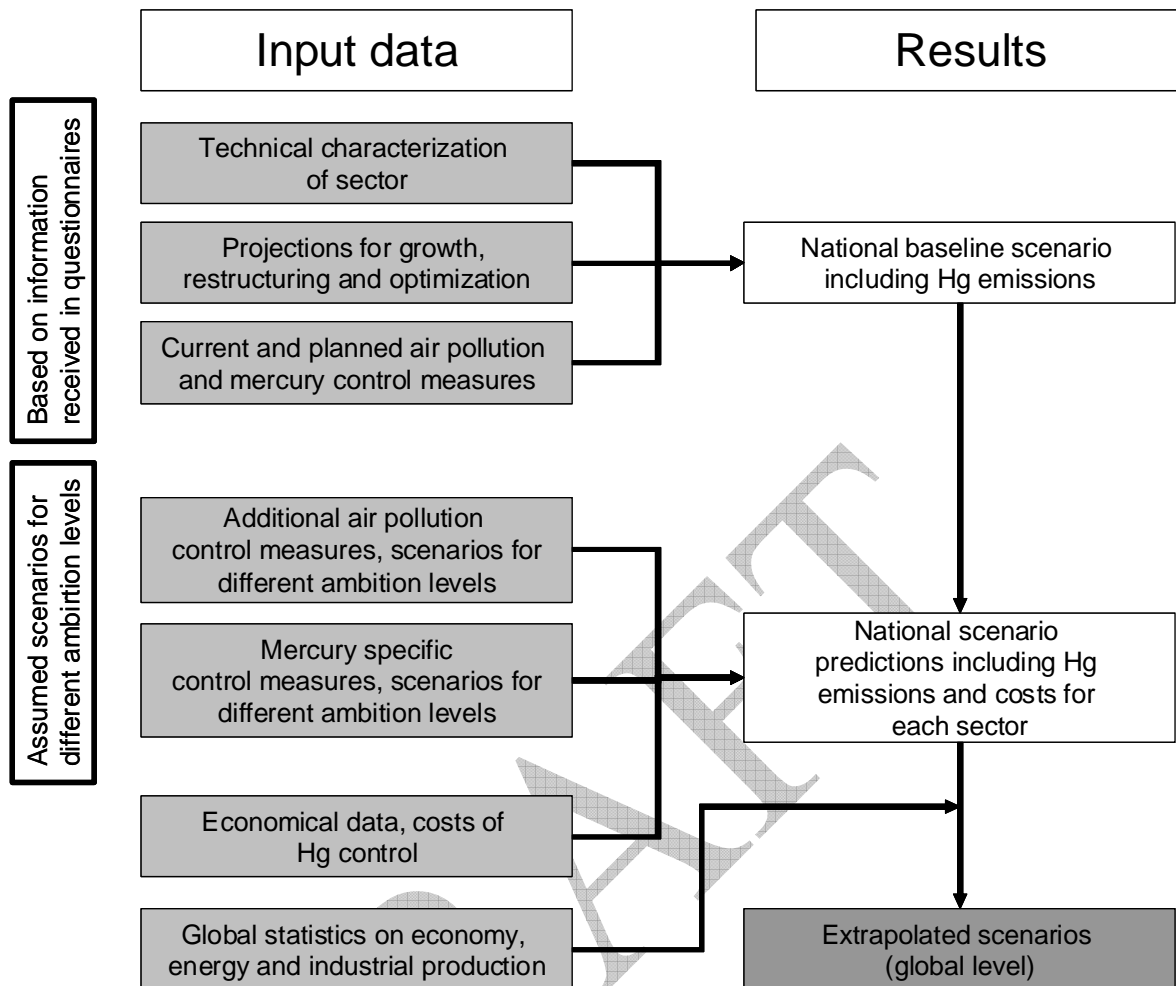
The main conclusions from Phase I of this study are:

- Mercury emissions from the selected sectors coal combustion in power plants and industrial boilers, cement production, non ferrous metal production and waste incineration contribute 51% to the total global emissions to air of mercury in 2005.
- An evaluation of global emission trends including a harmonisation of data and improved completeness of inventory indicate that global emissions have varied from 1967 tonnes in 1990, a slight decrease to 1814 and 1819 tonnes in 1995 and 2000, respectively, to 1921 tonnes in 2005.
- The lack of any major trend in global mercury emissions is a result of a significant shift between regions in the emissions. While Asian emissions have increased in the period 1990 to 2005, emissions in North America and Europe have decreased.
- The scenarios presented in this report indicate that large increases in global mercury emissions will occur if no measures are taken. For a Status Quo scenario i.e. when no further measures are taken to reduce mercury emissions, economical growth, increased energy demand and increased industrial production will lead to increases in global emissions from the by product sectors of 371 tonnes.
- Reduction of mercury emissions in the considered sectors can be achieved by a combination of pre-treatment of fuels, air pollution control measures (aimed at reducing SO<sub>x</sub> and particle emissions) and mercury specific control technologies (e.g. activated carbon injection). Since control technologies for air pollutants to some extent also reduce mercury emissions, information about current and future status of air pollution control is essential for the development of more realistic scenarios.
- A number of examples of cost estimates for measures to reduce mercury emissions to air are available and can be used as a basis for the development of scenarios for the selected sectors. Detailed information on source characterisation, mercury contents and composition of fuel and raw materials is however essential for a more detailed assessment of mercury control options, costs and efficiencies.

### **5.2. Continuation of the Para 29 study**

For the second phase of this study, information on source characterization, current and planned installations of air pollution control and national projections will be available. This will allow the development of more realistic scenarios also taking into account uncertainties in efficiencies and costs of control options.

The procedure of the second phase of the Paragraph 29 study will be based on a general approach, schematically presented in Figure 8:



**Figure 8.** Schematic description of procedure to derive scenarios for mercury emissions to air.

The procedure described in Figure 8 also depicts how the information submitted by the selected countries will be employed to derive the scenarios

The stepwise procedure for the preparation of the scenarios in Phase 2 of the study can be summarised in the following way:

**1. National emission inventory and technical descriptions for the selected sectors in the selected countries.** This will be based on the information reported in response to the questionnaires. If actual emission data are not available, emission estimates will be derived using available activity data and emission factors, and any available information on mercury contents in fuels and raw material, installed air pollution control, in consultation with national experts. The result of this first step is a baseline emission inventory for mercury, representing the current situation. Technical descriptions of the sectors will also be included here.

**2. National plans for development of sector.** This step includes the assessment of future plans for the selected sectors which may influence mercury emissions to air. Included here are plans for air pollution control, restructuring/modernization, predicted growth of sectors, Again basic

information is expected in response to the distributed questionnaires. Based on the submitted information, estimates of a baseline scenario for mercury emissions will be prepared.

**3. Selection of potential measures for national scenarios.** In this step, the information used in steps 1 and 2 is used to derive potentially applicable control strategies for reducing mercury emissions. Depending of the current and planned status of the sectors this may include both measures directed at air pollution control and specific measures to control mercury emissions. In the former case, the effect of air pollution control measures on mercury emissions to air will be assessed. The results of this step are a set of 2-3 scenarios with different ambition levels for mercury control.

**4. Evaluation of efficiencies and costs for national scenarios.** Based on the potential technical measures derived in step 3, the overall effects on mercury emissions and the associated costs for these measures will be estimated. 2-3 different scenarios representing different ambition levels will be prepared. Allocation of costs between control measures primarily intended for air pollution control and mercury specific measures will also be discussed here. along with uncertainties in the estimates.

**5. Extrapolation to global scenarios.** The final step of the scenario development is to extrapolate the results from the selected countries to the global scale. This will be done by combining the results with information on regional information on economical growth, status of the selected sectors and other parameters.

DRAFT

## 6. References:

- EC 2001a. IPCC Reference Document on Best Available Techniques in the Non Ferrous Metals Industries, European Commission, December 2001.
- EC 2001b. IPPC Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries, European Commission, December 2001.
- EC 2006. IPPC Reference Document on Best Available Techniques for Waste Incineration, European Commission, August 2006. [ftp://ftp.jrc.es/pub/eippcb/doc/wi\\_bref\\_0806.pdf](ftp://ftp.jrc.es/pub/eippcb/doc/wi_bref_0806.pdf)
- EMEP/EEA air pollutant emission inventory guidebook — 2009. EEA Technical report No 6/2009. <http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009>
- EPA 2009. National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry Federal Register / Vol. 74, No. 86 / Wednesday, May 6, 2009
- Feeley T.J. III, Brickett L.A., O’Palko A., Jones A.P. 2008, DOE/NETL’s Mercury Control Technology R&D Program Taking Technology from Concept to Commercial Reality, Presented at the MEGA Symposium, Baltimore, August 2008.
- GAO 2009. Mercury control technologies at coal-fired powerplants have achieved substantial emissions reductions. Report to the Chairman, subcommittee on Clean Air and Nuclear safety, Committee on Environment and Public Works, US Senate. GAO -10-47  
[http://en.wikipedia.org/wiki/Zinc\\_smelting](http://en.wikipedia.org/wiki/Zinc_smelting)
- Hageman, S. et al 2010. Technical and economic criteria for processing mercury-containing tailings. Report to UNEP February, 2010.
- IEA Clean Coal Centre, Coal online, <http://www.coalonline.org/site/coalonline/content/home>
- IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>
- Laudal, D., Thompson, J., Pavlish, J., Brickett, L., Chu, P., Srivastava, R., Lee, C., Kilgroe, J. (2002). Evaluation of mercury speciation at power plants using SCR and SNCR NO<sub>x</sub> control technologies. Proceedings, Air Quality III Conference, September 2002, [http://www.netl.doe.gov/publications/proceedings/02/air\\_q3/UNDEERC.pdf](http://www.netl.doe.gov/publications/proceedings/02/air_q3/UNDEERC.pdf)
- Pacyna, E.G. and J.M. Pacyna, 2002. Global emission of mercury from anthropogenic sources in 1995. *Water, Air and Soil Pollution*, 137: 149-165.
- Pacyna, J.M. and E.G. Pacyna, 2005. Anthropogenic sources and global inventory of mercury emissions. In: Parsons, M.B. and J.B. Percival (eds.), *Mercury: Sources, Measurements, Cycles, and Effects*. Mineralogical Association of Canada, Short Course Series Volume No. 32.
- Pacyna J.M., Sundseth K., Pacyna E.G., Munthe J., Belhaj M., Astrom S., Panasiuk D. and A. Głodek, 2008. Socio-economic costs of continuing the status-quo of mercury pollution, GLOCSA-SE report, Nordic Council of Ministers, TemaNord 2008:580, Copenhagen.
- Pacyna, J. M., Sundseth, K., Pacyna, E. G., and Jozewich, W., 2009. An Assessment of costs and Benefits Associated with Mercury Emission Reductions from Major Anthropogenic Sources. *Journal of Air and Waste Management Association* (Accepted).

- Panasiuk D., Pacyna J.M., Głodek A., Piątek R., Pacyna E.G., Strzelecka-Jastrzab E., Fudała J. and S. Hławiczka, 2006. Scenarios for heavy metals, dioxins/furans and PCBs emissions to air in Europe for years 2010 and 2020, DROPS D1.2 Report, Katowice,
- Pavlish J H, Sondreal E A, Mann M D, Olson E S, Galbreath K C, Laudal D, Benson S A (2003) Status review of mercury control options at coal-fired power plants. *Fuel Processing Technology*; 82 (2-3); 89-165 (Aug 2003)
- Rokke, N., 2006. The Energy Outlook of Norway. Plenary session presentation of the Polish-Norwegian Energy Supply and Environmental Impact Thematic Seminar 18 October 2006. PowerPoint presentation.
- Sloss, L. (2008). Economics of mercury control. Clean Coal Center, CCC/134
- Srivastava R K, Hutson N, Martin B, Princiotta F, Staudt J (2006) Control of mercury emissions from coal- fired utility boilers. *Environmental Science and Technology*; 40 (5); 1385-1393 (Mar 2006)
- UNEP, 2005. Toolkit for identification and quantification of mercury releases. UNEP chemicals branch, mercury programme.  
<http://www.chem.unep.ch/mercury/Toolkit/default.htm>
- UNEP/AMAP, 2008. Technical Background Report to the Global Atmospheric Mercury Assessment. Arctic Monitoring and Assessment Programme /UNEP Chemicals Branch. 159 pp.  
([http://www.chem.unep.ch/mercury/Atmospheric\\_Emissions/Technical\\_background\\_report.pdf](http://www.chem.unep.ch/mercury/Atmospheric_Emissions/Technical_background_report.pdf))
- UNEP, 2008. UNEP Report on A general qualitative assessment of the potential costs and benefits associated with each of the strategic objectives set out in Annex 1 of the report of the first meeting of the Open Ended Working Group, UNEP Chemicals Branch, UNEP-CBA report.  
[http://www.chem.unep.ch/mercury/OEWG2/documents/e52\)/English/OEWG\\_2\\_5\\_add\\_1.pdf](http://www.chem.unep.ch/mercury/OEWG2/documents/e52)/English/OEWG_2_5_add_1.pdf)
- UNEP Chemicals Branch, 2008. The Global Atmospheric Mercury Assessment: Sources, Emissions and Transport. UNEP-Chemicals, Geneva. 42 pp.  
([http://www.chem.unep.ch/mercury/Atmospheric\\_Emissions/UNEP%20SUMMARY%20REPORT%20-%20final%20for%20WEB%20Dec%202008.pdf](http://www.chem.unep.ch/mercury/Atmospheric_Emissions/UNEP%20SUMMARY%20REPORT%20-%20final%20for%20WEB%20Dec%202008.pdf))
- UNEP POG, in prep. Process Optimization Guidance Document for Reducing Mercury Emissions from Coal Combustion in Power Plants. Report to UNEP Chemical Branch, January 2010.
- Visschedijk A.J.H., Denier van der Gon H.A.C., van het Bolscher M. and P.Y.J. Zandveld, 2006. Study to the effectiveness of the UN ECE Heavy Metals (HM) Protocol and cost of additional measures. TNO report No. 2006-A-R0087/B, Apeldorn, the Netherlands.