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A NOVEL COMBINATION OF METHODS DEVELOPED FOR DECISION SUPPORT ON ABATEMENT OF MERCURY IN EUROPE

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LIST OF ACRONYMS AND ABBREVIATIONS

ACI *Activated Carbon Injection*

AMAP *Arctic Monitoring and Assessment Program*

AMBIO *Scientific Journal, see reference list*

APCD *Air Pollution Control Device*

As *Arsenic, chemical symbol*

ASGM *Artisanal Small-scale Gold Mining*

BAT *Best Available Techniques*

BATT *Batteries containing mercury*

BAU+ *Business as Usual with Climate Policies, scenario assumption*

Climate

BO *Basic oxygen*

Br *Bromine, chemical symbol*

BREF *Best Available Techniques Reference Documents*

By product *Emissions from primary anthropogenic sources*

CCC *Clean Coal Centre of the IEA*

Cd *Cadmium, chemical symbol*

CEE *Center for Ecology and Economics*

CFL *Compact Fluorescent Lamp*

CLRTAP *A convention on air pollution under the UN Economic Commission*

CMAQ-Hg *Cloud chemistry model*

Co- benefit *Auxiliary benefit which occurs beyond the emission reduction target*

CO *Carbon monoxide*

Convention *Convention on Long-Range Transboundary Air Pollution*

Cr *Chromium, chemical symbol*

Cu *Copper, chemical symbol*

DALY *Disability- adjusted life year*

Dent *Dental uses of mercury*

DG	*Directorate- General, the European Commission*
DOE	*US Department of Energy (USA)*
DRF	*Dose- Response Function*
DROPS	*Development of macro and sectoral economic models aiming to evaluate the role of public health externalities on society, Research project funded by European Union*
DSS	*Decision Support System*
EA	*Electric arc*
ECE	*Economic Commission for Europe*
Elec	*Electric and electronic devices containing mercury*
EMEP	*European Monitoring and Evaluation Programme*
EPER	*EU25 European Pollutant Emission Register*
EPRI	*Electric Power Research Institute*
E-PRTR	*European Register of Pollutant Release and Transfer*
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 Emission Control*
FBC	*Fluidized Bed Combustion*
FDA	*Food and Drug Administration (USA)*
FF	*Fabric Filter*
FGD	*Flue Gas Desulphurization*
FOA	*Food and Agriculture Organization*
	for Europe (UN ECE)
GAO	*Government Accountability Office (USA)*
GDP	*Gross Domestic Product*
GEM	*Gaseous Elemental Mercury*
GEOS-Chem	*Simulation model run by the GEOS-Chem steering committee*

GLEMOS *Simulation model developed by MSC East*

GRAHAM *Simulation model developed by Environment Canada*

GTCC *Gas combustion in combined cycle gas*

HALY *Health- adjusted life year*

HEIMTSA *Research project funded by European Union, see reference list*

HELCOM *Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area*

Hg *Mercury*

Hg^0 *Elemental mercury*

$HgCl_2$ *Mercuric Chloride*

Hg-P *Particulate associated mercury*

IE *Industrial Ecology, a scientific discipline*

IEA *International Energy Agency*

IECM *Integrated Environmental Control Model*

IGCC *Integrated gasification combined cycle*

IMERC *Interstate Mercury Education and Reduction Clearinghouse (USA)*

INC *Intergovernmental Negotiating Committee*

iPOG *Software developed in the connection with the UNEP process optimization guidance document on coal combustion*

IPCC *International Panel on Climate Change*

IPPC *Integrated Pollution Prevention and Control, a EU directive*

IQ *Intelligence Quotient*

Lamp *Lamps and light bulbs containing mercury*

LED *Light- Emitting Diodes*

LRTAP *Convention on Long-range Transboundary Air Pollution*

Meas *Measuring equipment containing mercury*

MeHg *Methylmercury (short for monomethylmercury $[CH_3Hg]^+$)*

MFTR *Maximum Feasible Technology Reduction*

Mn *Manganese, chemical symbol*

MSCE-HM	*Heavy Metals simulation model developed by MSC East (Russia)*
MWh	*Megawatt hour (energy generation)*
MWhe	*Megawatt hour electricity*
NCM	*Nordic Council of Ministers*
NESCAUM	*Northeast States for coordinated air use management (USA)*
NETL	*National Energy Technology Laboratory*
NGO	*Non- governmental Organization*
NH_3	*Ammonia*
NILU	*Norwegian Institute for Air Research*
NO_X	*Nitrogen Oxides*
NPV	*Net Present Value*
O&M	*Operating and Maintenance (used when describing costs)*
O^3	*Ozone*
OEWG	*Open- ended Working Group (under UNEP administration)*
OH	*Hydroxyl radical; Open heart furnace*
OSPAR	*Oslo and Paris Convention for the Protection of Marine Environment of the North-East Atlantic*
PAC	*Powdered Activated Carbon*
PARCOM	*Paris Commission for the Prevention of Marine Pollution from land- based Sources*
Pb	*Lead, chemical symbol*
PCC	*Pulverized Coal Combustion*
PM	*Particulate Matter*
POG	*Process Optimization Guidelines see reference list*
PPP	*Purchase Power Parity*
QUALY	*Quality- adjusted life year*
REACH	*The European Community Regulation on chemicals and their safe use*
RGM	*Reactive Gaseous Mercury (divalent)*
RoHS	*European directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment*

Sb	*Antimony, chemical symbol*
SCR	*Selective Catalytic Reduction*
Se	*Selenium, chemical symbol*
SFA- diagram	*A diagram illustrating flows of substance*
SFA	*Substance Flow Analysis*
SNCR	*Selective Non-Catalytic Reduction*
SO_2	*Sulphur Dioxide*
SQ	*Status Quo*
TGM	*Total Gaseous Mercury*
UNEP	*United Nations Environmental Programme*
US EPA	*United States Environmental Protection Agency (USA)*
V	*Vanadium, chemical symbol*
VCM	*Vinyl Chloride Monomer*
VOC	*Volatile Organic Compounds*
VOLY	*Value of Life Year*
VSL	*Value of Statistical Life*
WCED	*World Commission on Environment and Development*
WFD	*Water Framework Directive*
WTP	*Willingness- to-pay*
Zn	*Zinc, chemical symbol*

INTRODUCTION

Mercury (Hg) emitted in the EU (European Union) region are highly toxic to humans, animals and ecosystems. High doses organic compounds, and particularly methylmercury (MeHg) can be fatal to humans but even relatively low doses can seriously affect the human nervous system and has been linked with possible harmful effects on the cardiovascular, immune and reproductive systems. Methylmercury passes through both the placenta and the blood-brain barrier, so exposure of women of child-bearing age and of children to methylmercury is of greatest concern. Consequently, several studies have been conducted on the behavior of mercury in the environment and its environmental and economic consequences associated with its presence. A synthesis of the most important such studies are presented in a special issue of AMBIO, (2007) on mercury pollution.

Mercury poses in general a global problem. It is persistent, meaning that it does not degrade in the environment. It is mobile because of the volatility of the metal and several of its compounds. It has the ability to cross international borders, predominantly transported in the atmosphere. Finally, it bio-accumulates (particularly in arctic regions), and ultimately becomes a threat to human health via the food chain. It is, therefore, a matter of international concern. The need for cooperative action is recognized in the EU Mercury Strategy (launched in 2005 and reviewed in 2010) and the international actions underway that support and encourage global action on mercury reduction. The EU"s Mercury Strategy provided a comprehensive plan incorporating actions addressing mercury pollution both in the EU and globally. It identified a variety of actions to reduce mercury emissions, cut supply, reduce demand and protect against exposure, especially to methylmercury found in fish. The strategy resulted in restrictions on the sale of measuring devices containing mercury, a ban on exports of mercury from the EU (that recently came into force), and new rules on safe storage. An overview of EU regulations and directives on mercury emissions can be observed in the Appendix.

International actions underway that support and encourage global action on mercury reduction is mainly linked to UNEPs (United Nations Environmental Programme) initiative and goal of developing a global convention on mercury which would create a legally binding instrument on mercury prior to 2013. The EU countries are (through the European Commission) leading this process of negotiations, and it is expected implementation of the instrument`s targets in the years following 2013[1]. An important phase in deriving a common strategy that the European Commission can take forward to the international negotiations will be identifying and analyzing their alternative policy options already in place as well as possible future options for reducing mercury emissions. This involves collecting

[1] Details on the negotiation process as well as relevant background information are available at the UNEP website: http://www.unep.org/hazardioussubstances/Mercury/Negatiations/tabid/3320/Default.aspx (visited August 2011).

information on effectiveness and economic implications of measures to reduce anthropogenic emissions and to do this within a sound scientific framework. Furthermore, this will allow the EU to take a proactive stance to ensure that it puts in place policy options that represent the best cost-effective measures for the control and reduction of risks associated with mercury. Advances in scientific based knowledge the last decades has lead to a better basis for informed decision making as several studies have been conducted on emission sources and the behavior of mercury in the environment and its environmental and economic consequences associated with its presence.

In the following sub- chapters, the most recent (state of the art) scientific knowledge obtained by the candidate together with other members of the NILU team is summarized on 1) global emissions, 2) physical linkages between these emissions and deposition, followed by 3) emission trends and future emission scenarios, and 4) their economic implications in terms of increased or reduced environmental and human exposure. Finally, 5) research on the costs and feasibility of mercury emission reductions in selected major mercury source sectors is presented.

THEORETICAL PART

1 State of the art

1.1 Global mercury emissions to the atmosphere

On request from the UNEPs Governmental Council, a global anthropogenic emission inventory on mercury to the atmosphere in 2005 was carried out by the candidate together with other members of the NILU team. This resulted in the report; Global Atmospheric Mercury Assessment: Sources, Emissions and Transport (UNEP, 2008a), presented at the UNEPs OEWG (Open- Ended Working Group) in Nairobi, 2007. The report is to date regarded as the most comprehensive such inventory presented. The emission results have been peer reviewed in Pacyna et al., (2010a).

Anthropogenic activities leads in general to mercury being mobilized from its long- term geological storage into the biosphere and further emitted to the environmental compartments; air, water and soil, often at high concentrations. Since mercury does not degrade; the environmental concentrations are increasing in line with enhanced anthropogenic activities. Anthropogenic sources of mercury globally can be distinguished as *primary anthropogenic sources* and *secondary anthropogenic sources.*

Primary anthropogenic sources are those where mercury of geological origin is mobilized by human activities and unintentionally released to the environment. The two main source categories in this group are mining (both for mercury and for other minerals) and extraction and burning of fossil fuels which contain mercury as a trace contaminant. The sources comprise; 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; chlor- alkali industry using the mercury- cell process and certain „other‟ sources. Primary anthropogenic sources also include waste incineration, although the mercury in the waste is already used as a commodity, i.e. the mercury is intentionally introduced to in products entering the waste streams.

Secondary anthropogenic sources are those where emissions occur from the intentional use of mercury, including mercury use in industrial processes, in products, in dental applications, or in artisanal and small-scale gold mining (ASGM) operations.

Primary natural sources are related to the mercury that occurs naturally in the earth‟s crust which releases via weathering of rocks and as a result of geothermal and volcanic activities. A significant amount of atmospheric mercury may also be naturally emitted or re- emitted (or re-mobilized) from soil- and vegetation-, as well as water and sea surfaces. Mercury that is being re- emitted includes emissions caused by anthropogenic activities at present and in the past (e.g. Mason and Sheu, 2002; Selin et al., 2007). It is difficult, however, to establish the amount of mercury in the air that is due to re- emission as they typically are included under natural emission estimates. Depending on assumptions made in models, it has been suggested that primary anthropogenic sources contribute from approximately 30% (Selin et al. 2007)) to 60% (Lamborg et al. 2002)) of the total mercury emissions.

1.1.1 Mass balance studies

Comprehensive mercury air-ocean-soil models have been presented in Lamborg et al. (2002), Mason and Sheu (2002), and in Sunderland and Mason (2007). Lamborg et al. (2002) developed their model using the inter-hemispheric gradient of total gaseous mercury and sediment historical archives of mercury deposits as the main constraints to constructing pre-industrial and current global budgets of mercury. Mason and Sheu (2002) compiled data on speciation of mercury in the atmosphere, aquatic and terrestrial fluxes and sediments and bog records of atmospheric deposition to describe the pre-industrial and current global budgets of mercury. These studies estimate a 3-fold increase in mercury in the atmosphere and up to 2-fold increase from pre-industrial to present time. The oceans were at the same time found to play an important role in cycling the anthropogenic mercury.

The most recent global mercury air-ocean-soil model presented in Sunderland and Mason (2007), estimated that approximately 134 000 tons of mercury resides in the global upper oceans, and about 5600 tons in the atmosphere. These reservoirs include pollution- related enhancement of about 25% and 300-500%, respectively, relative to the pre- industrial period (AMAP, 2011). Their model revealed a temporal lag between changes in atmospheric deposition and ocean mercury concentrations from decades to centuries. Figure 1(from Sunderland and Mason, (2007)) illustrates a comprehensive picture of pre-industrial and present-day global budgets of mercury on Earth.

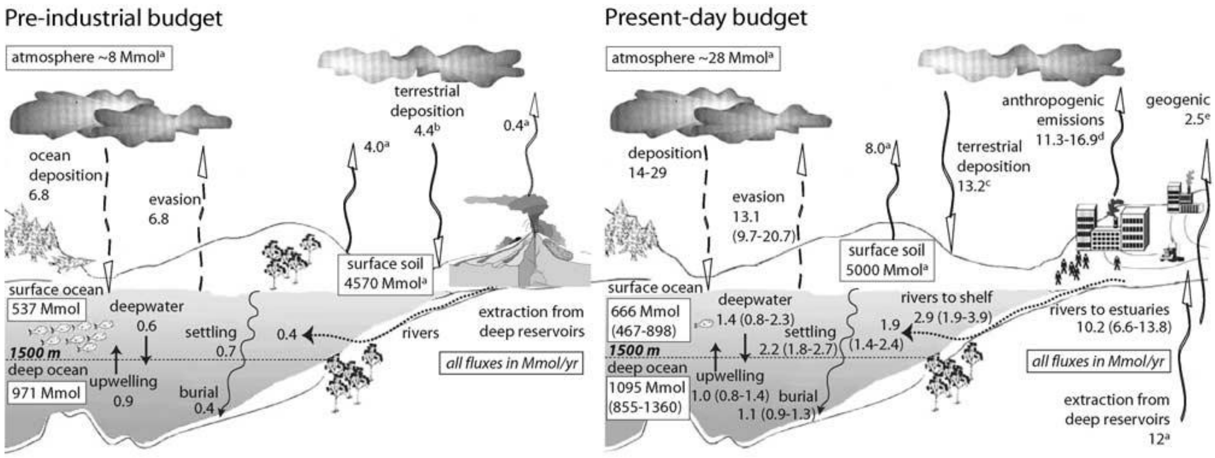

Figure 1 Pre-industrial and present-day global budgets of mercury on Earth (Source: Sunderland and Mason, 2007)

1.1.2 Anthropogenic emission sources

The total global anthropogenic emissions in the year 2005 were estimated by the candidate and other members of the NILU team as about 1930 tonnes. A later update in UNEP, (2010) has reduced this estimate to about 1920 tonnes, mainly resulting from an adjustment of ASGM emissions in China. Figure 2 illustrates the breakdown of mercury emissions by continent and the major emission sectors.

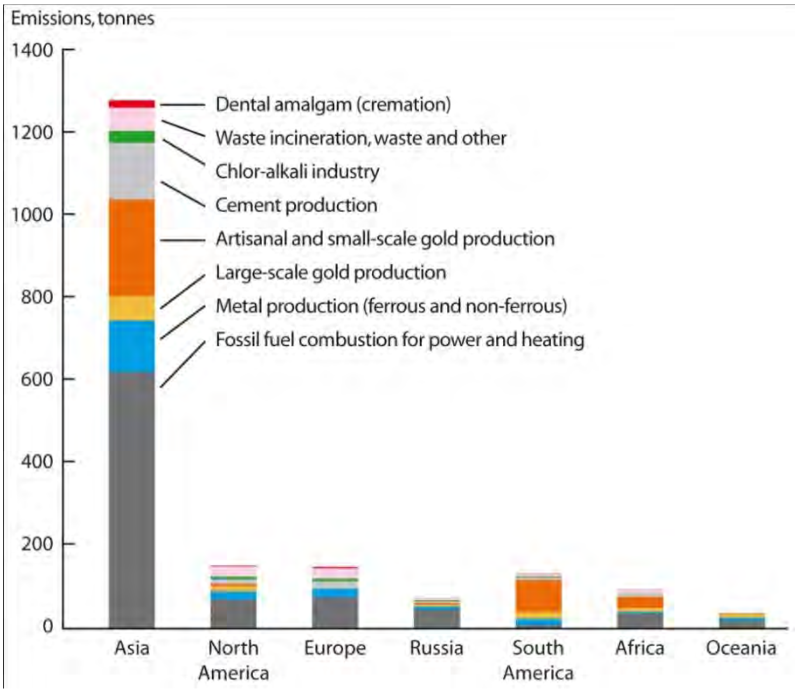

Figure 2 Emissions of mercury to air in 2005 from various anthropogenic sectors in different regions. (Source: Pacyna et al., 2010a)

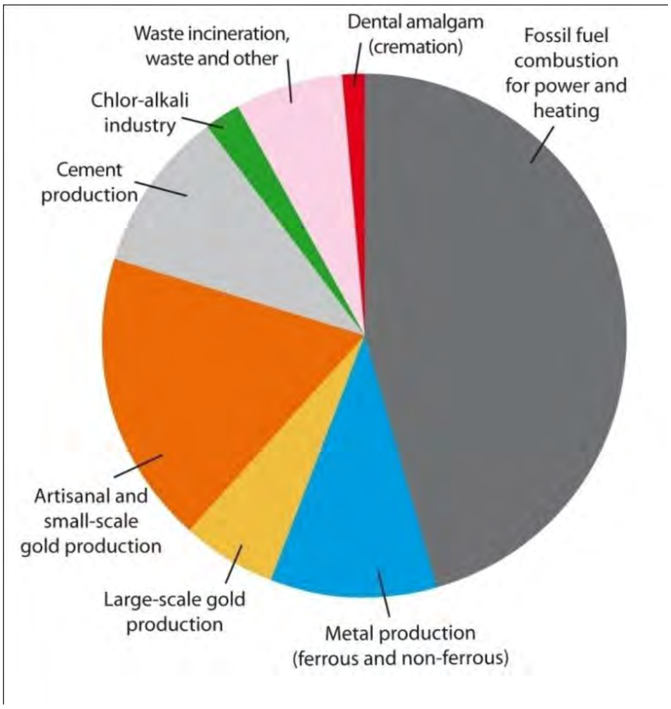

Figure 3 Proportion of global anthropogenic emissions of mercury to air in 2005 from various sectors (Source: Pacyna et al., 2010a).

From Figure 2 it is apparent that Asian countries contributed the most (about 67%) to the global mercury emissions from anthropogenic sources in 2005, followed by North America and Europe. This pattern is similar if only primary anthropogenic emission sectors are considered. Russia, with its contribution of about 4% to global emissions was considered separately due to its territories in both Europe and Asia.

Combustion of fuels to produce electricity and heat is the largest source of anthropogenic mercury emissions in Europe, North America, Asia and Russia, and responsible for about 40–50% of the anthropogenic emissions in Oceania and Africa. However, in South America ASGM is responsible for the largest proportion of the emissions (>55%).

Stationary combustion of coal, and to a lesser extent other fossil fuels, associated with energy or heat production in major power plants, small industrial or residential heating units or small-scale residential heating appliances as well as various industrial processes, is the largest single source category of anthropogenic mercury emission to air, accounting for more than 880 tonnes worldwide. Although coal does not contain high concentrations of mercury, the amount of coal that is burned and the fact that emissions from coal-burning plants mainly goes to the atmosphere makes coal burning the largest anthropogenic source of mercury emissions to the atmosphere (Pacyna et al., 2010a).

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, and at mine sites through accelerating the exposure of tailings to natural weathering processes. Mining and processing of mercury is a relatively minor source. Production of gold, where mercury is both present in ores and used in some industrial processes to extract gold from lode deposits, however, can be a significant source (e.g. Swain et al., (2007)). The major source of atmospheric mercury related to the iron and steel industry is the production of metallurgical coke.

The third major source of primary anthropogenic releases of mercury is associated with cement production, where mercury is released primarily as a result of combustion of fuels to heat cement kilns.

ASGM remains the largest global use sector for mercury. It reportedly continues to increase with the upward trend in the price of gold and is the largest source of environmental release from intentional use of mercury. ASGM is inextricably linked with issues of poverty and human health. According to Telmer, (2008), at least 100 million people in over 55 countries depend on ASGM – directly or indirectly – for their livelihood, mainly in Africa, Asia and South America. ASGM is responsible for an estimated 20 to 30% of the world"s gold production.

The large and increasing use of mercuric chloride as a catalyst in the production of vinyl chloride monomer (VCM), notably in China, is another area of major concern, especially as it is not yet clear how much mercury – estimated to be several hundred tonnes per year – is released via flue gases, to the hydrochloric acid waste stream, and during the recycling of depleted catalyst (e.g. Swain et al., 2007).

The chlor-alkali industry is the third major mercury user worldwide. Many plant operators have phased out this technology and converted to the more energy-efficient and mercury-free membrane process, others have plans to do so, and still others have not announced any such plans. In many cases, governments have worked with industry representatives and/or provided financial incentives to facilitate the phase-out of mercury technology. Major issues still relate to the fate of stocks of mercury recovered from the chlor-alkali industry as the mercury process is phased out (e.g. EC, 1997).

The use of mercury in batteries, while still considerable, continues to decline. Many countries have implemented policies to mitigate the problems related to diffuse mercury releases such as those associated with disposal of mercury-containing batteries. While mercury use in Chinese batteries was confirmed to have been high through 2000, most Chinese manufacturers have reportedly now shifted to designs with lower mercury content, following international legislation and trends in customer demand in other parts of the world (NRDC, 2006).

Mercury can be released to the environment as a result of routine losses during handling of mercury in dental applications, and following cremation of human remains with dental mercury. In some higher income countries dental use of mercury is now declining as alternatives such as composites (most common), glass ionomers and compomers (modified composites) are introduced.

A wide selection of mercury-containing measuring and control devices, including thermometers, barometers and manometers are still manufactured in various parts of the world, although mercury-free alternatives are available for nearly all such applications and increasingly being used. This change to mercury-free alternatives is being reinforced by legislation in some regions, such as Europe. The global estimate for mercury consumption in these applications is based heavily on Chinese production of sphygmomanometers and thermometers (SEPA, 2008). Over 270 tonnes of mercury were estimated to have been used in the production of only these two devices in 2004, with China responsible for about 80 to 90% of world production of these two products. Thermometers and sphygmomanometers are considered to represent around 80% of total mercury consumption in this sector.

Mercury-containing lamps (fluorescent tubes, compact fluorescent, high-intensity discharge lighting) remain the standard for energy-efficient lamps, where ongoing industry efforts to reduce the amount of mercury in each lamp are countered, to some extent, by the ever-increasing number of energy-efficient lamps purchased and installed around the world. There is no doubt that mercury-free alternative, such as LEDs (light-emitting diodes) will become increasingly available, but for most applications the alternatives are still quite limited and/or quite expensive.

Owing to the RoHS Directive (for the restriction of the use of certain hazardous substances in electrical and electronic equipment) in Europe, and similar initiatives in Japan, China and California, among others, mercury-free substitutes for devices such as mercury switches and relays are being actively encouraged, and mercury consumption has declined substantially in recent years. At the same time, the US-based Interstate Mercury Education and Reduction Clearinghouse (IMERC) database demonstrates that mercury use in these devices remains significant.

The category „other applications of mercury" has traditionally included the use of mercury and mercury compounds in such diverse applications as pesticides, fungicides, laboratory chemicals, pharmaceuticals, as a preservative in paints, traditional medicine, cultural and ritual uses, and cosmetics (DG ENV, 2008).

1.1.3 Global distribution of anthropogenic emissions in 2005

The global emissions presented for the year 2005 estimated by the candidate were provided as input data to be geo-spatially distributed within a global 0.5 x 0.5 degree latitude/longitude grid. In the absence of comprehensive information on the locations of emission sources, the geo-spatial exercise involved the use of population distribution[2] (see Wilson et al., 2006) with the underlying assumption is that the more people that are located in a given area, the more mercury is emitted in that area. To reduce uncertainty, new „distribution masks" were prepared in addition to global population masks; these included an „urban population" mask, an „industrial activity" mask, a major power plant mask, and a gold deposits mask. Information on the mercury emissions from anthropogenic sources is geospatially distributed and presented in emission maps by a 0.5 x 0.5 degree grid in Figure 4. Similar maps are available in UENP, (2008a) for three main types of mercury compounds: gaseous elemental mercury (Hg^0, GEM), divalent mercury compounds (Hg^{2+}, RGM), and particulate associated mercury (Hg-P, TPM) at three emission height classes (emissions below 50 m, between 50 and 150 m, and above 150m).

[2] The limitations of the use of population as a „distribution mask" for distributing mercury emissions are discussed in Wilson et al. (2006).

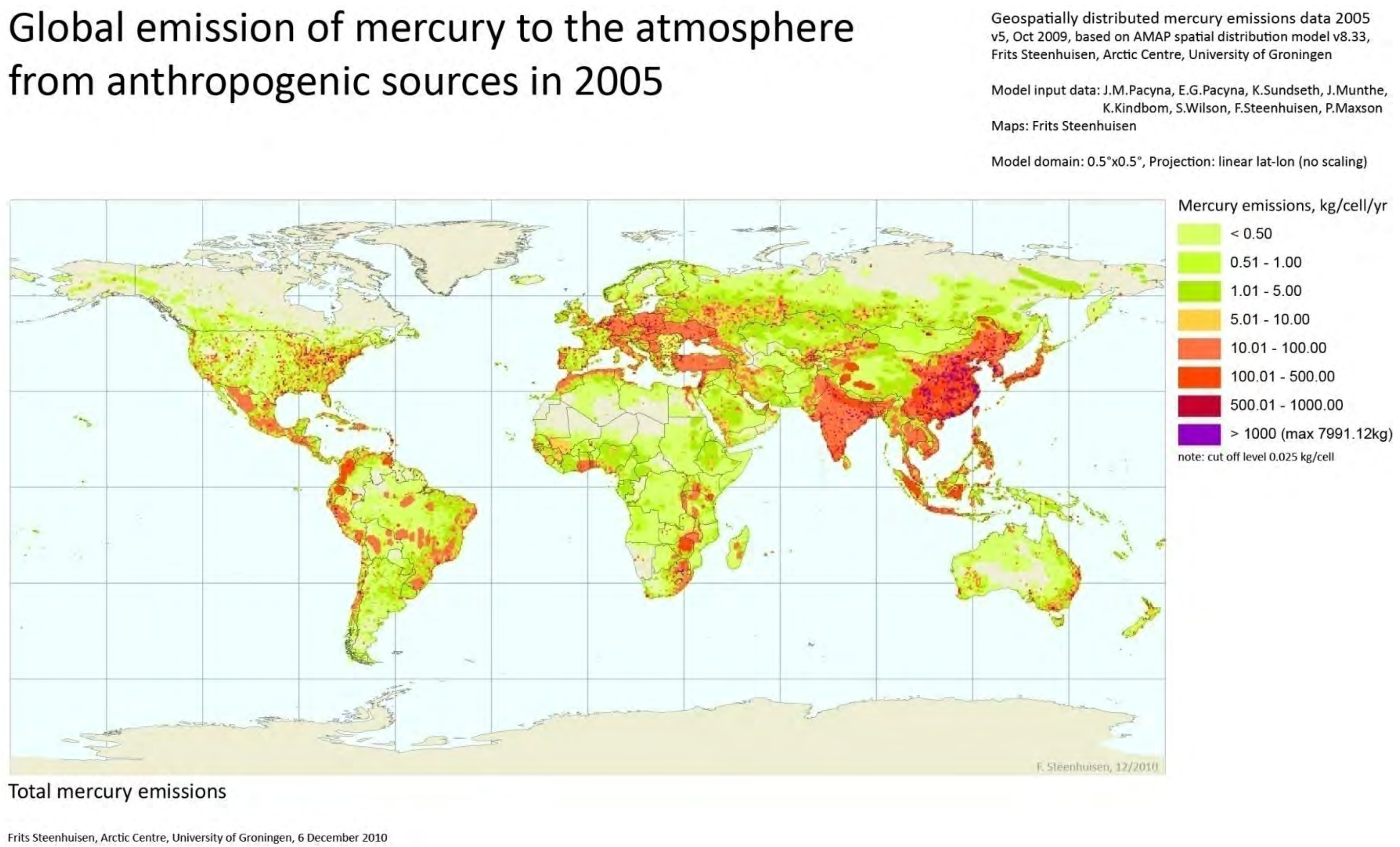

Figure 4 Global emission of mercury to the atmosphere from anthropogenic sources in 2005, geospatially distributed (Source: Frits Steenhuisen).

1.1.4 Global trends

1.1.4.1 Mercury emission trend

As part of the AMAP 2010 assessment of mercury in the Arctic, the candidate contributed to a re-analysis of the 1990-2005 global mercury inventories in an attempt to prepare a series of more comparable historical global emission inventories (AMAP, 2010). This re-analysis employed a common methodology, a more consistent information base for estimating certain emissions, and updating of the earlier inventories to account for improved knowledge gained during the process of preparing the inventories. The re-analysis also involved correcting some estimates in older inventories according to updated information on practices and technologies. 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 secondary anthropogenic emission sectors. Revised estimates (regional trends) of total emissions of mercury to air in 1990, 1995, 2000 and 2005 from primary and secondary anthropogenic emission sectors are presented in Figure 5.

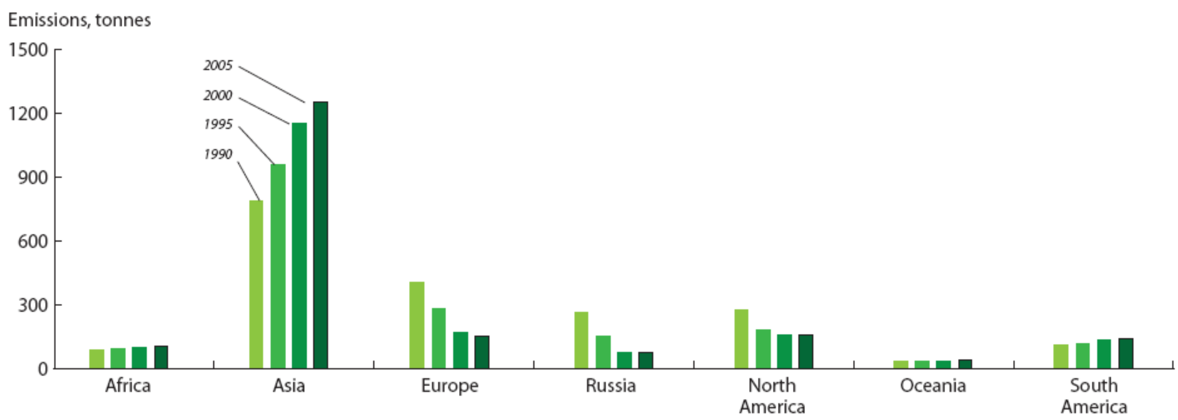

Figure 5 Revised estimates of yearly anthropogenic mercury emissions to air (tonnes) in 1990, 1995, 2000 and 2005 from different continents/regions (Source: AMAP 2010).

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. Figure 5 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.

1.1.4.2 Deposition trend

Travnikov and Ilyin (2008) estimated long-term changes in mercury deposition in different regions of the northern hemisphere using the MSCE-HM mercury model. They simulated the period 1990 to 2004 using emission datasets available for the years 1990, 1995, and 2000 (e.g. Pacyna et al., 2006).

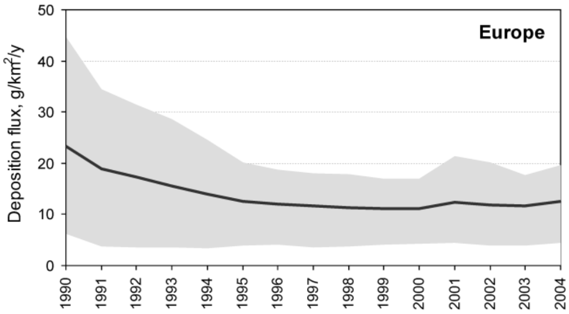

Figure 6 Deposition trends for Europe (Source: Travnikov and Ilyin (2008)).

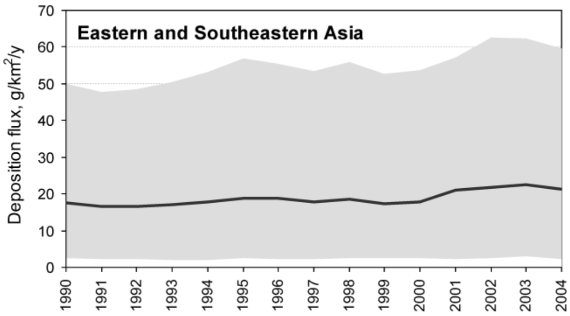

Figure 7 Deposition trends for Eastern and Southeastern Asia (Source: Travnikov and Ilyin (2008))

They found that the most significant decrease in deposition took place in Europe. The average deposition flux in Europe decreased by half, whereas the highest deposition decreased by almost two-thirds (Figure 6). Analysis shows that this reduction is mainly due to considerable emission reductions in Europe during this period. Changes in mercury deposition in North America are less pronounced because of smaller emission reductions and a higher relative contribution from other continents (in particular, from Asia). At the beginning of the period deposition levels in East and Southeast Asia were comparable to those in Europe, whereas by the end of the period deposition in Asia had become the highest in the northern hemisphere (Figure 7).

1.1.5 Global emission scenarios

As long as global economic activities continue to increase, and current patterns, practices and uses are maintained, mercury pollution will undoubtedly increase in the future. There are however, various ways to reduce mercury emissions and their negative consequences on the environment and human health. Often the question is how to allocate limited resources towards reducing mercury emissions in the most cost- efficiently manner possible.

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 prepared by the candidate and other members of the NILU team (e.g. in Pacyna, 2010a) 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; however, emission control practices remain unchanged from those currently employed, leading to increased emissions from several sectors.
- The „Extended Emissions Control" (EXEC) scenario assumes economic progress at a rate reflecting the future development of industrial technologies and emissions control technologies; that is, mercury-reducing technologies currently generally employed throughout Europe and North America would be implemented elsewhere. It further assumes that emissions control measures currently committed to in Europe to reduce mercury emissions to air or water would be implemented throughout the world. These include certain measures adopted under the LRTAP Convention Heavy Metals Protocol, EU Directives, and also agreements to meet International Panel on Climate Change (IPCC) Kyoto targets on reduction of greenhouse gases causing climate change (which indirectly will result in reductions in mercury emissions).
- 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.

The assumptions made for mercury for the year 2020 is presented in UNEP, (2008a). Scenario estimates of primary anthropogenic mercury emissions in 2020 for the three scenarios: SQ, EXEC and MFTR and different regions are presented in Figure 8. The 2005 emission estimates are also presented in this figure for comparison.

If no major changes in the efficiency of emission control are introduced and economic activity continues to increase (the SQ scenario), significant increases in global anthropogenic mercury emissions (equivalent to about one quarter of the 2005 mercury emissions from these sectors) are projected in 2020. The largest increase in emissions of mercury is projected for stationary combustion, mainly from combustion of coal. A comparison of the 2020 emissions estimated from the EXEC scenario and the SQ scenario indicates that a further 1000 tonnes of mercury could be emitted globally on top of the projected emission of 850 tonnes (under the EXEC scenario) in 2020, if mercury continues to be emitted under the control measures and practices that are in operation today against a background of increasing population and economic growth in some regions. In other words, the implementation of available measures and practices (the basic assumption of the EXEC scenario), implies a benefit of reducing mercury emissions by up to 1000 tonnes per year in the period to 2020 under the assumptions employed in this scenario discussion. Doing nothing to improve reduction of mercury emissions is projected to result in emissions in 2020 that are more than 100% above those envisaged under the EXEC scenario.

As might be expected, an even greater reduction in mercury emissions is projected if the 2020 SQ scenario is compared with the 2020 MFTR emission reduction scenario. In this comparison or projections, emissions of mercury in various industrial sectors, such as cement production and metal manufacturing by the year 2020 could be 2- to 3-fold higher if nothing is done to improve emission control.

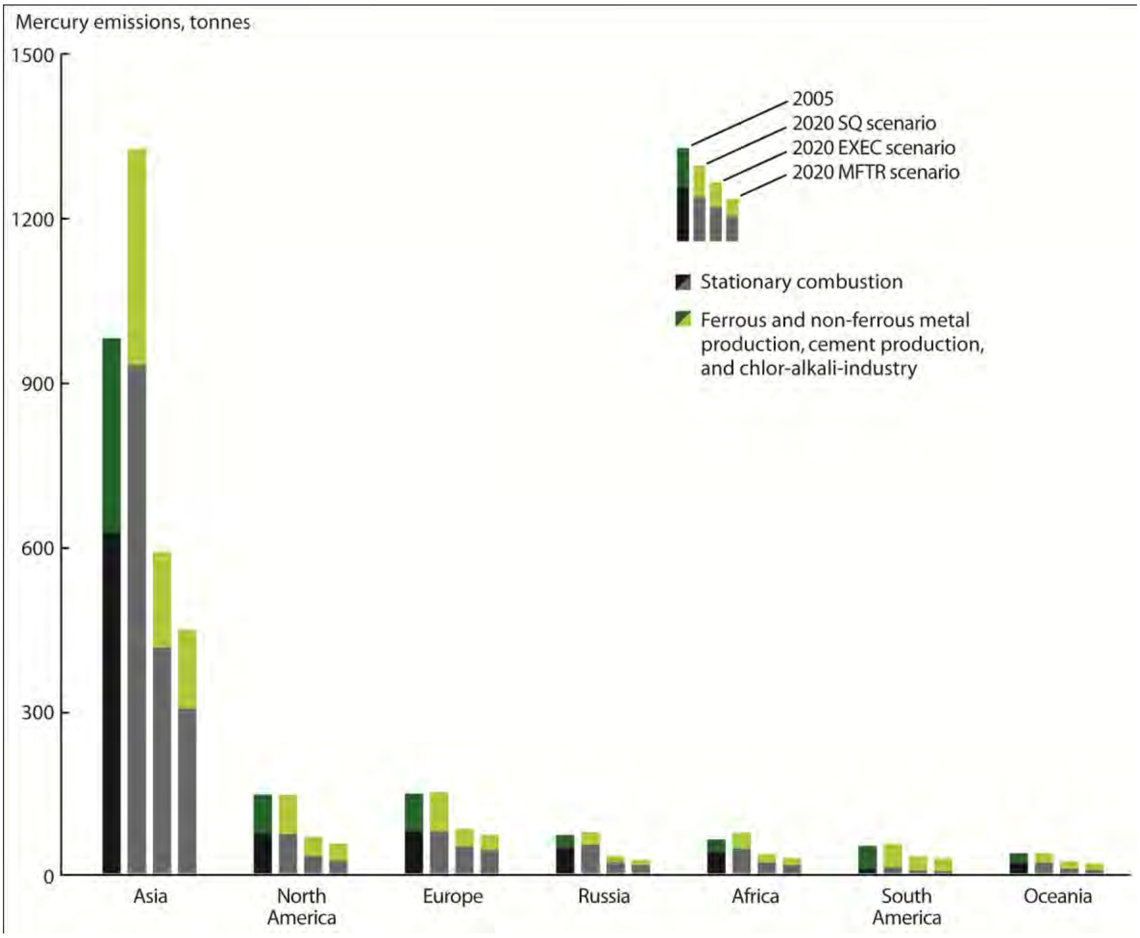

Figure 8 Comparison of anthropogenic emissions (in tonnes per year) of mercury from the 'primary anthropogenic' plus chlor-alkali sectors in 2005 and under the 2020 SQ, EXEC and MFTR scenarios (Source: Pacyna et al., 2010a).

Under the EXEC scenario, clear decreases in mercury emissions 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 projected decreases in mercury emissions in Europe, North America, Australia, Japan and Russia are between 40 and 60 %.

Scenarios for future intentional use of mercury are highly uncertain due to the lack of consistent international agreements or policies to reduce mercury demand. In many countries and regions, large efforts are nevertheless being made to reduce mercury use in products and in industrial applications. The potential for reduction of use is also large since technologically and economically feasible alternatives are often available.

Two future scenarios for mercury consumption in different categories were defined in Pacyna et al., (2010). The scenarios were based on a partly qualitative discussion of reduction potentials and ongoing activities to reduce demand. To take into account the unavoidable uncertainties, two different scenarios were considered: a „Status Quo scenario" and EXEC („focused mercury reduction") scenario". For the Status Quo scenario, data on use and emissions presented by Pirrone and Mason (2008) were used. In addition, an MFTR scenario was developed, based on an overall assumption of 50% reduction of mercury use in comparison to the EXEC scenario. For ASGM, no change in consumption is assumed beyond that envisaged in the EXEC scenario. This assumption reflects the expected difficulties in managing this largely unregulated sector. Table 1 presents projected future trends for emissions from intentional use of mercury.

Table 1 Emissions of mercury (in tones) from intentional use in three 2020 emission scenarios.

	SQ 2020	EXEC 2020	MFTR 2020
ASGM	330	164	164
VCM	N.A.	N.A.	N.A.
Batt	20	5	3
Dent	25	16	11
Meas	33	9	5
Lamp	13	9	5
Elec	26	11	6
Other	29	3	1
Sum	**475**	**218**	**195**

ASGM – Artisanal Gold Mining, VCM - Vinyl Chloride Monomer, Batt – Batteries, Dent – Dental use, Meas – Measurement equipment, Lamp – Lamps and light bulbs, Elec – Electrical and electronic equipment.

It should be noted that the scenarios presented above are hypothetical and the future trends in mercury consumption are highly dependent on the development of legislation or voluntary agreements to reduce mercury usage. The reduction potential is large, perhaps even larger than reflected in the MFTR scenario in some cases, but actual compliance is difficult to estimate.

1.2 Atmospheric pathways, transport and fate

1.2.1 Atmospheric pathways and transport

Mercury is mainly emitted to the atmosphere in the form of GEM. Minor amounts are either emitted as RGM or as TPM. GEM has a relatively long lifetime in the atmosphere (currently believed to be between 0.5 and 1.5 years), being slowly oxidized to either reactive gaseous mercury or total particulate mercury (see Figure 9). The two latter species have much shorter lifetimes (hours to days) and are therefore subject to fast removal by wet or dry deposition. It is thus reasonable to see more regional effects from primary sources emitting these species as they tend deposited closer to the source. Because of the local removal of RGM and TPM, the highest depositions of mercury are found close to emission sources in Europe, North America and East Asia (Christensen et al., 2004; Dastoor and Larocque, 2004). Although under certain conditions some TPM may be subject to long-range transport.

The atmospheric reactions of mercury are critical to determine how mercury is transported in the atmosphere and where it is deposited. There is ongoing scientific debate about the reactions that may be responsible for removing GEM from the atmosphere and large efforts have been devoted to the study of the chemical removal of GEM. Oxidants like ozone (O^3) and hydroxyl radical (OH) can be important reactants for the removal of GEM (Hall, 1995; Sommar et al., 2001; Pal and Ariya, 2004a, b; Sumner and Spicer, 2005). GEM may also be transported to particles and oxidized by O3 in the particles (Munthe, 1992). The reaction with OH is leading to an HgOH intermediate. The gas phase reaction of GEM with bromine (Br) is emerging as an important reaction in the global atmosphere. This reaction starts a sequence of reactions that eventually lead to RGM. The reaction sequence is temperature-dependent (Goodsite et al., 2004) and the fastest removal of GEM is observed under cold conditions such as those prevailing at the poles or in the upper part of the troposphere, whereas much longer lifetimes are found at warmer temperatures.

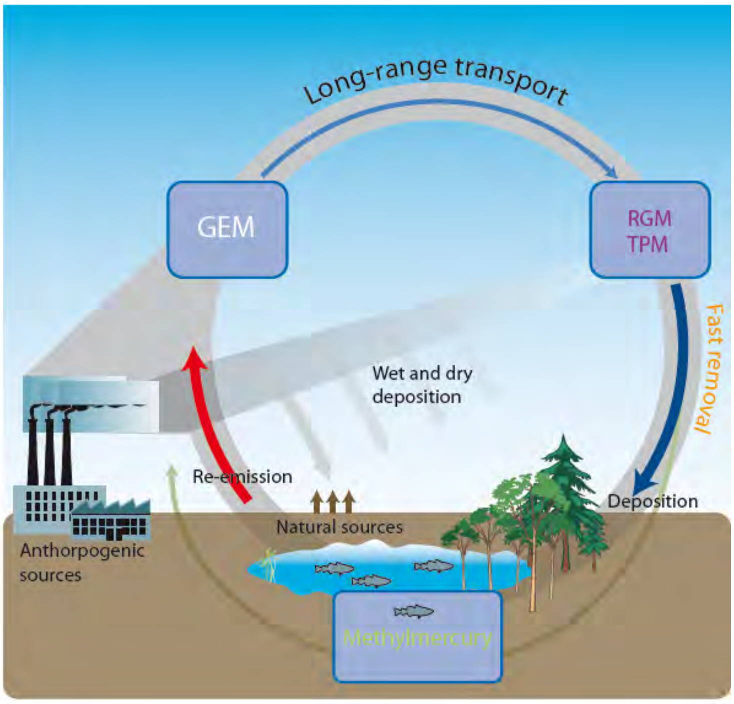

Figure 9 Schematic descriptions of emission, chemical transformation and deposition of atmospheric mercury (Source: UNEP, 2008a).

Deposited mercury can be converted back to elemental mercury by chemical reactions (reduction reactions) in the soil or water or by bacteria, or alternatively can be converted by bacteria to methylmercury – but in either case, the result may be re-emission of mercury to the atmosphere. Mercury is therefore one of the pollutants that can be transported by a so-called „multi-hop" process involving repeated cycles of transport–deposition–re-emission. One result of this is that mercury, even mercury originally emitted as RGM or TPM and deposited close to sources, can be transported towards colder regions (where re-emission is less pronounced). Concentration profiles in peat, sediments and ice cores in the Arctic show that there is an increased deposition of mercury today compared to the pre-industrial period, with an apparent maximum in deposition occurring between the 1950s and the 1970s. There is a general qualitative agreement between the deposition profiles in environmental archives and emission inventories.

1.2.2 Fate

1.2.2.1 Mercury air concentrations and deposition patterns

Current knowledge on mercury dispersion on a global scale and levels of mercury concentration and deposition in different parts of the globe are illustrated in Figure 10 and Figure 11 below. The figures are based on simulation results of the GRAHM model, coordinated by the candidate for the AMAP mercury Assessment report (AMAP, 2011). The model conducted simulations of mercury global or hemispheric dispersion for 2005 using the most suitable model parameterizations and input data. Details of the model can be found in Dastoor and Davignon, (2008).

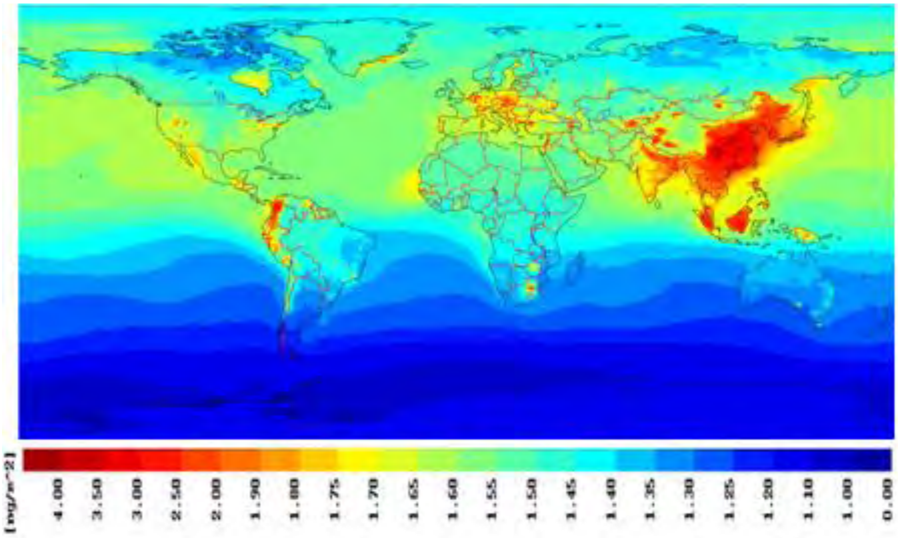

Figure 10 Total gaseous mercury average concentrations (Source: AMAP, 2011).

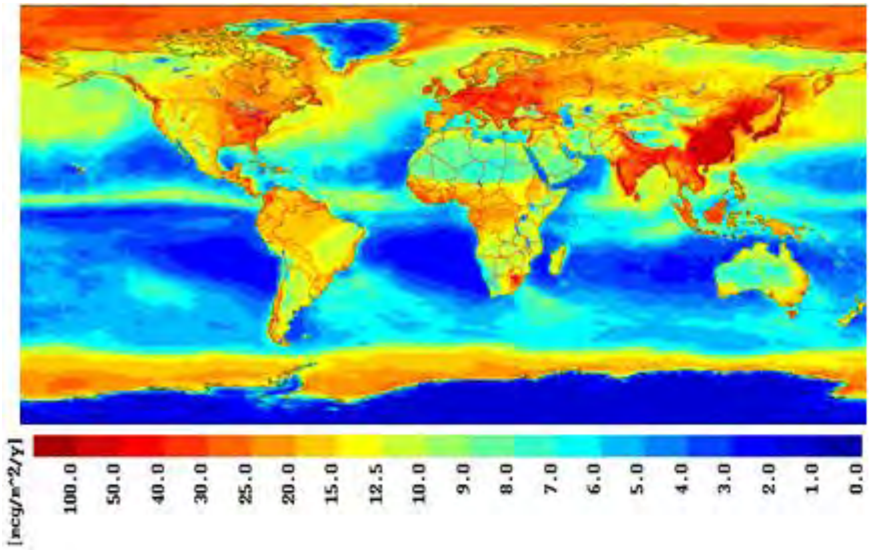

Figure 11 Total gaseous mercury yearly depositions (Source: AMAP, 2011).

It has been concluded (e.g. in UNEP 2008a) that contemporary models successfully reproduce elemental mercury concentrations in the ambient air (i.e. uncertainty does not exceed 15–20%). Uncertainty of model simulation of short-lived mercury species is much higher and is directly connected with uncertainty of mercury deposition. Processes governing mercury deposition are poorly known and uncertainty of simulated total depositions is much higher – a factor of two. The largest contribution to the deposition uncertainty is made by dry deposition. The most significant factors affecting uncertainty of mercury deposition include emissions data (anthropogenic and natural), parameters of chemical reactions leading to oxidation of elemental mercury to short-lived forms, and characteristics of dry deposition.

1.2.2.2 Source- receptor relationships

Source attribution of mercury depositions have been studied in a number of previous studies. Relative importance of global versus regional sources and source-receptor relationships were evaluated in the GLEMOS model (HTAP, 2010). The multi- model simulations determined for instance that about 40% of annual mercury deposition (including natural emission sources) to Europe originated from external sources including 19% from Asia, 4% from Africa and North America, and 3% from South America and Australia. From 15% to 25% of the atmospheric mercury deposited in Europe originates from primary anthropogenic emission sources elsewhere in the world. The results can be observed in Figure 12.

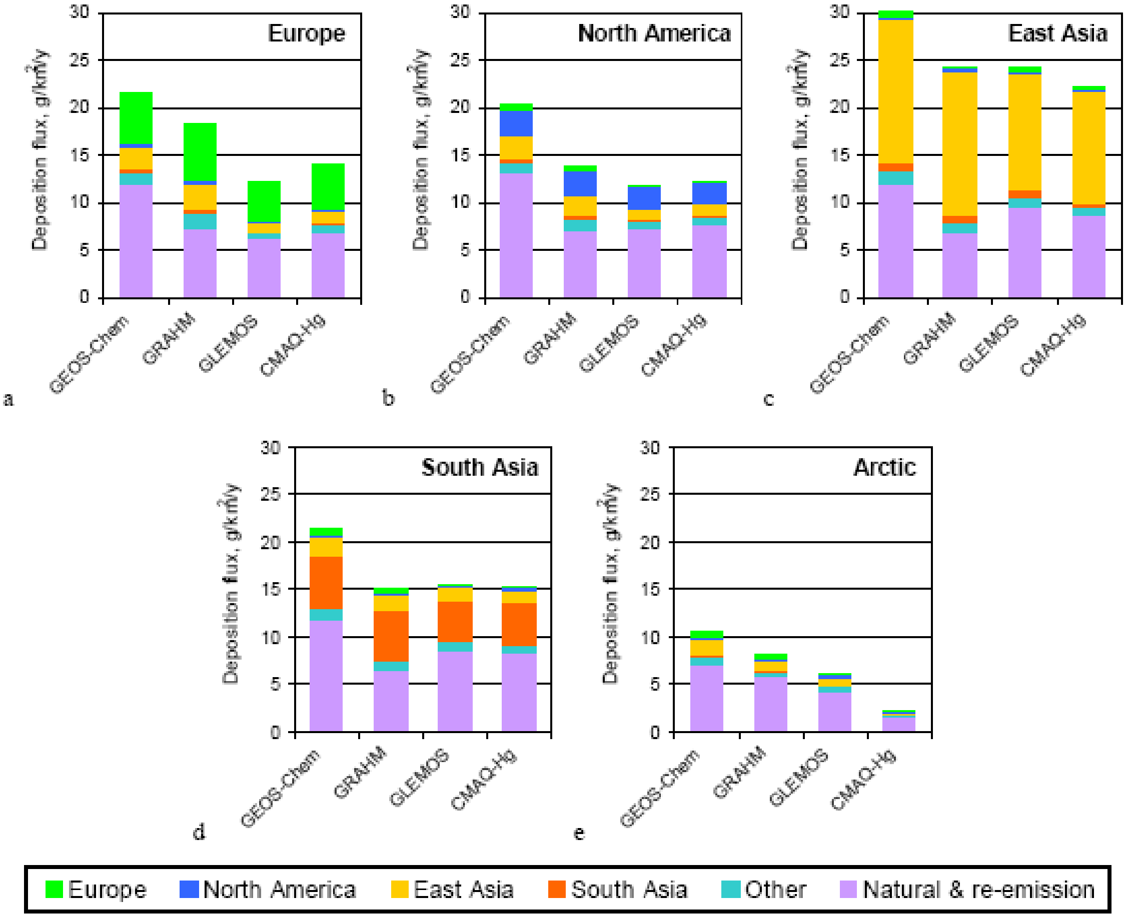

Figure 12 Relative importance of global versus regional sources and source- receptor relationships as presented in (Source: HTAP, 2010).

1.2.2.3 Mercury fluxes under the scenario assumptions

The candidate has coordinated and prepared parts of the 2011 AMAP Mercury Assessment on how the projected changes in global mercury emissions will affect the levels in the Arctic atmosphere and ocean. Modeling of the annual average concentrations of TGM in the air and average annual atmospheric deposition in the year 2005 and 2020 modeled by the GRAHM model are presented in Figure 13 and Figure 14 (AMAP, 2011). It should be noted that the model estimates were performed assuming no change in the pattern and direction of air mass transport in the year 2020 compared to the year 2005. Thus, no impact of climate change on this pattern is taken into account.

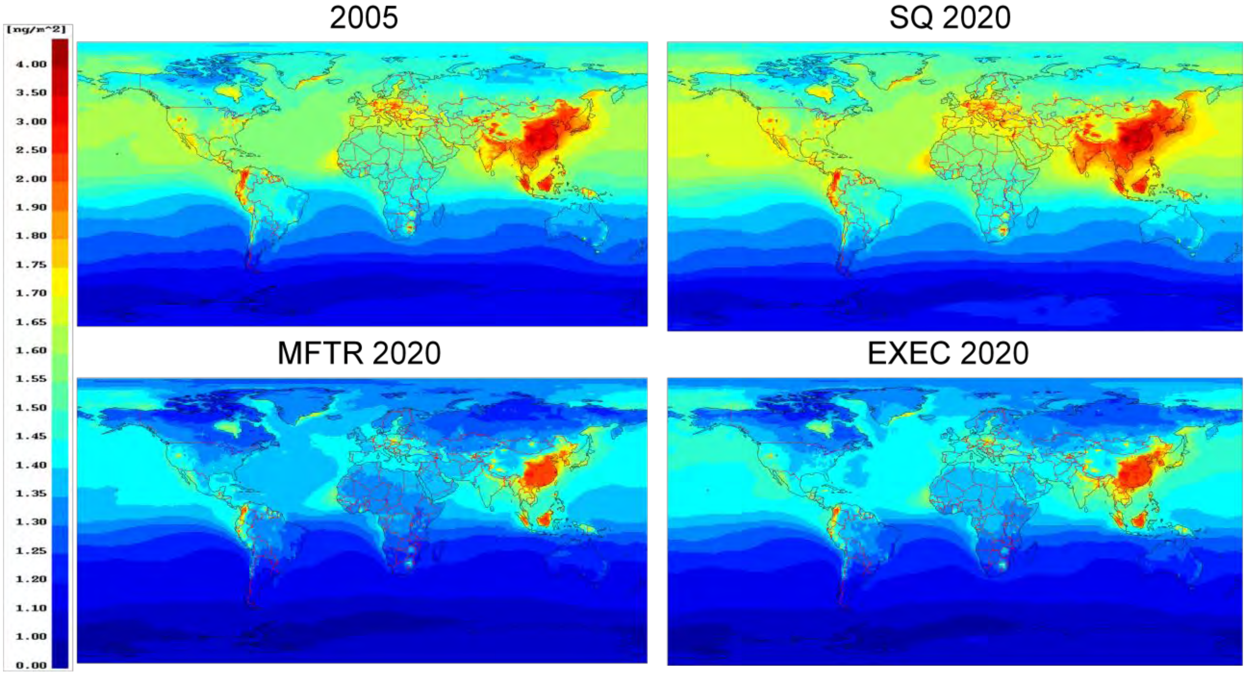

Figure 13 Yearly TGM average concentrations (Source: AMAP, 2011).

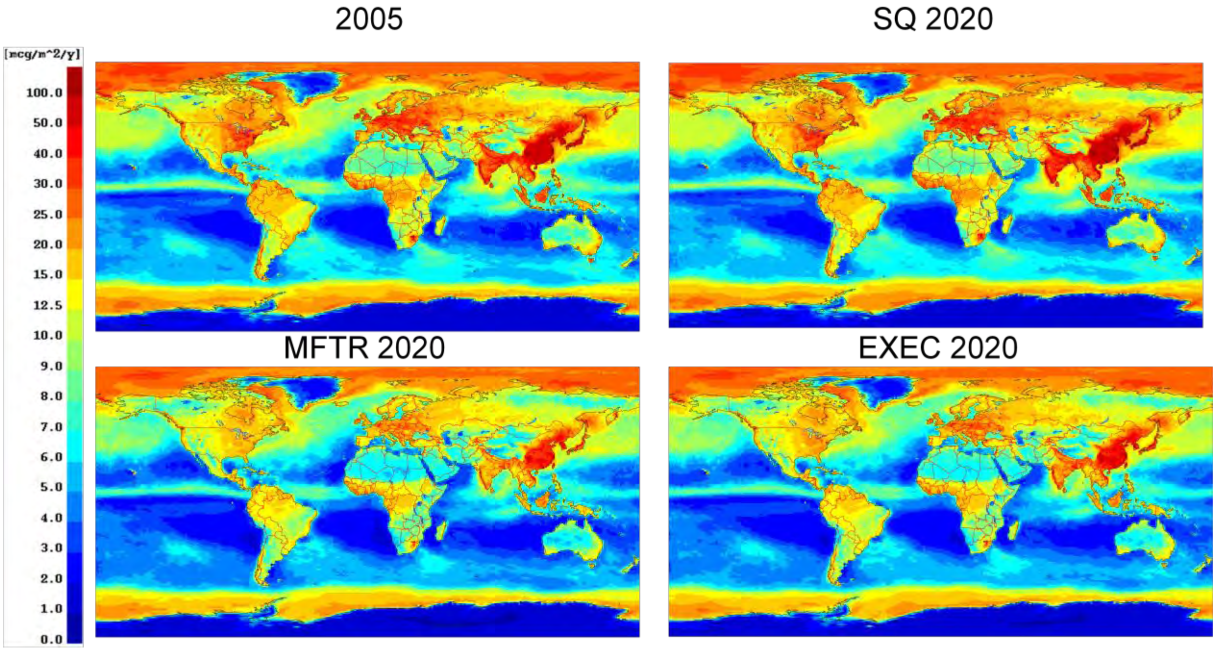

Figure 14 Total yearly mercury depositions (Source: AMAP, 2011).

Clear increase of both, air concentrations of TGM and atmospheric deposition of total mercury is seen between the years 2005 and 2020 using the SQ scenario, particularly in regions where the highest mercury emission occur or are expected to occur in 2020 along the SQ scenario. These regions include south-east Asia, Europe, incl. the European part of Russia, north-east North America (for atmospheric deposition) and north-west South America (for air concentrations). The largest increase of up to 20 % of concentrations of mercury in 2020 can be expected in south-east Asia, where the most of the emissions occur today, if no major action is taken to reduce current emissions (the SQ scenario). Interestingly enough, the increase of Hg in the atmospheric deposition in this region can be even up to 30-40 %, indicating that a significant portion of emitted mercury is deposited locally.

In contrary, the levels of mercury in air and atmospheric deposition will be lower in 2020 compared to the year 2005 if the reduction of mercury emissions will take place. Obviously, larger reductions of air concentrations and atmospheric deposition are expected within the MFTR scenario compared to the EXEC scenario due to larger Hg emission decreases estimated for the MFTR scenario. Concentrations of mercury in the air are expected to decrease up to 20 % in the most polluting regions of the world if the EXEC scenario emissions are applied in the model and slightly more if the MFTR scenario emissions are used. Reduction of up to 30 % are estimated in atmospheric deposition of Hg in south-east Asia, and north-east North America if the EXEC emission scenarios are used in the model. This reduction reaches even 40 % if the MFTR emission scenario is considered.

It could be noted that the 2005 emissions were estimated to increase by 25 % until the year 2020 along the SQ scenario. These emissions are expected to decrease by up to 40 % within the EXEC scenario and up to 50 % within the MFTR scenario.

1.2.2.4 Source- receptor relationships under the scenario assumptions

Relative contribution of major source regions to mercury deposition in year 2005 and according to the three emission scenarios for 2020 (SQ, EXEC, and MFTR) were presented in HTAP (2010) as average of modeling result from the GEOS-Chem, GRAHM, GLEMOS, and CMAQ-Hg models. The candidate`s work were used as input data to the modeling. Current (2005) and future changes of intercontinental transport are illustrated in Figure 15 (as presented in HTAP, 2010).

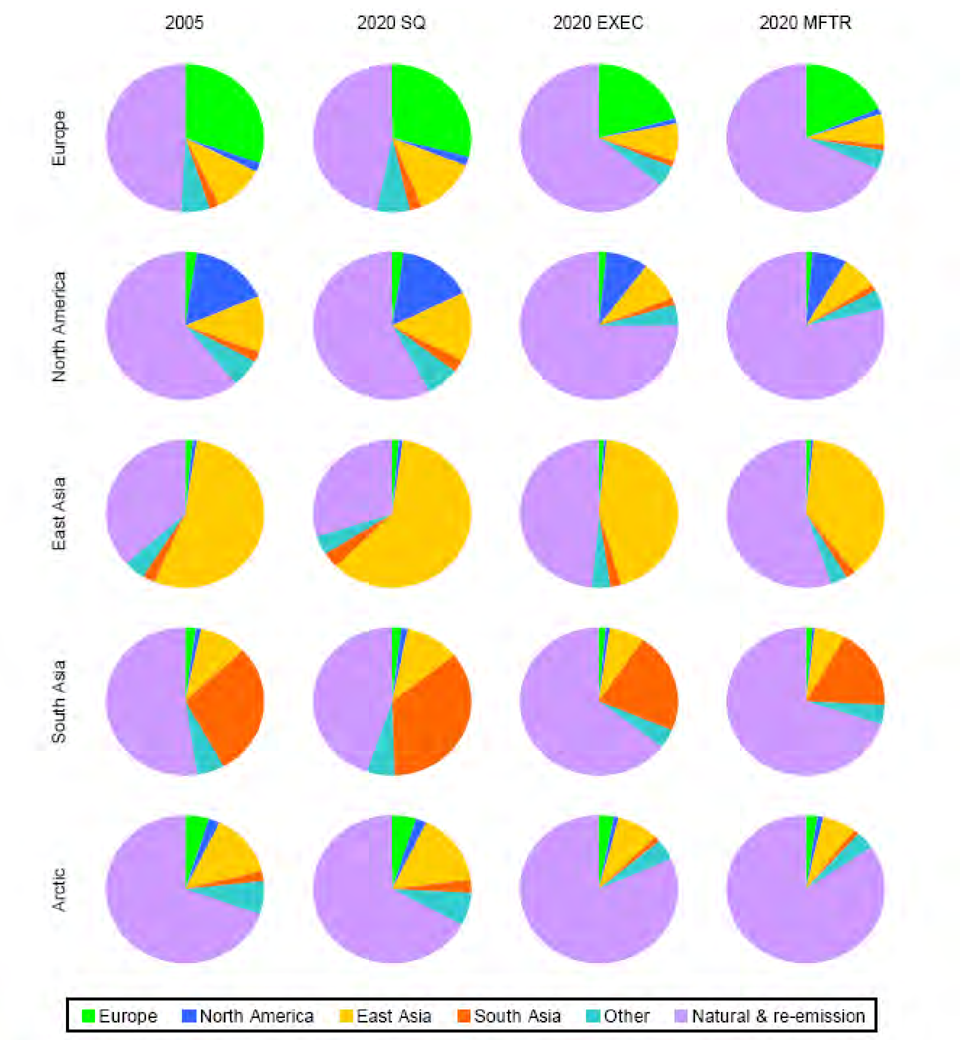

Figure 15 **Average relative contributions of major source regions to mercury in 2005 and according to the 2020 SQ, EXEC, and MFTR scenario as presented in (Source: HTAP, 2010).**

1.3 The potential risk from mercury emissions

It has been concluded that concentrations of mercury in ambient air are generally too low to represent any risk of health effects for humans. The concern over mercury in the environment is primary related to its potential of being transported over long distances by air or water currents. A small portion of the mercury is converted to methylmercury, which bio- accumulates in food-webs to levels that can be dangerous to organisms, including humans. Consumption of fish is thus the major source of methylmercury exposure to humans.

Various reference doses with regard to the optimum safe level of methylmercury content in fish have been proposed by various organizations, such as the Food and Agriculture Organization (FAO), the European Commission, Health Canada, the U.S. Food and Drug Administration (FDA), and the US EPA, ranging from 0.1 to 0.4 µg of methylmercury per kg of body weight per day (FOA, 2003). Populations who regularly and frequently consume large amounts of fish are more highly exposed.

A major assessment of the environmental effects of mercury that has been carried out within AMAP, concludes at the same time that some Arctic animal species, in particular marine top predators (such as toothed whale, polar bears and some bird species), experience levels of mercury in their tissues and organs that are believed to exceed thresholds for biological effects (AMAP, 2011).

Recent studies have shown that in addition to fish consumption, production of rice and vegetables at contaminated sites may also be contributing to enhanced methylmercury exposure (Zheng et al., 2007; Feng and Wui, 2008). This contribution to MeHg exposure tends to be dominated by local sources of contamination and is thus not important for intercontinental emission sources.

Deposition increases of mercury above threefold have been documented near emission sources; depositions depend on stack height, the quantity and chemistry of the emitted mercury, and local atmospheric chemistry (Lindberg et al., 2007; Swain et al., 2007). Aquatic systems vary, however, in the efficiency with which atmospherically-deposited mercury is transformed to methylmercury and bio- accumulated (Munthe et al., 2007). For example, the mercury concentration of fish in adjacent lakes can vary as much as 10-fold, even when atmospheric mercury levels are comparable (Weiner et al., 2006). The methylmercury levels in fish depend on atmospheric loading rates, ecosystem- specific properties, and food- web structure. In a given aquatic system, the production of methylmercury is believed to be approximately proportional to atmospheric mercury deposition (but with variable response time and magnitude).

1.3.1 Human health impacts caused by mercury emissions

Dietary methylmercury affects the nervous system it can causes neurological effects, including reductions in IQ among children. Because the developing fetus is the most sensitive to the effects from methylmercury, women of childbearing age are regarded as the population group of greatest concern (Mergler et al., 2007). No significant correlation with neurotoxin impacts has been found due to the lower sensibility of the adult brain (Weil et al., 2005). Among adults, neurobehavioral effects can be observed however, at moderately elevated exposures. There is also a body of evidence indicating elevated risk for cardiovascular diseases, especially myocardial infarction. In the case of severe exposure, there is a risk for reproductive outcomes, immune system effects and premature death (Mergler et al., 2007, Rae and Graham, 2004).

Associations between exposure and neurotoxin impacts in children has been observed from studies that followed cohorts of children among three populations in New Zealand (Kjellstrom et al., 1986), the Seychelles (Myers et al., 2003), and the Faroe Islands (Grandjean, et al., 1997), where diets contains a particularly large portion of seafood. Based on these findings, Trasande et al. 2005 consider several possible forms of the dose-response function (DRF) with and without threshold effect in estimating the societal cost of the IQ decrement in the USA. These DRFs were revised in Trasande et al. 2005. The revised function of DRF for mercury by Axelrad et al. (2007) is based on an integrated analysis of the New Zealand, the Seychelles, and the Faroe Islands studies as well as the estimates of Trasende et al. 2005. This function is also used in the Spadaro and Rabl, 2008 study.

The slope factor (i.e. the number of IQ point losses due to daily (yearly) intake of MeHg) in the Spadaro and Rabl, 2008 study, is a product of the relation between intake dose of methylmercury and concentration, maternal blood concentration, a ratio cord blood concentration, a ratio hair/cord blood, and a dose-response function for IQ loss per increase in maternal hair mercury. The result is a slope factor with a value of 0.036 IQ points per µg/day.

Quoting further Spadaro and Rabl, 2008, the lifetime impact on the offspring is only the product of the slope factor and ingestion above the threshold dose. Assuming the threshold dose of 6.7 µg/day, the effect is 0.020 IQ points loss while it is 0.087 IQ points loss for zero thresholds.

1.3.2 Damage costs caused by mercury emissions

An analysis on the damage costs of global mercury emissions has been done by the candidate on socio- economic cost of continuing the status quo of mercury pollution, initially prepared for the Nordic Council of Ministers (NCM, 2008). Economic damage cost estimates are based on the external costs associated with measurable damages to human health. The costs of human health damages are directly related to the dose of methylmercury received through the ingestion of polluted food during pregnancy that links to effects on the developing fetuses of the unborn child. The effects have shown to result in changes in the child"s IQ. Reduced IQ can have a future negative economical impact through reduced job attainment and performance, as well as educational achievement, which, in turn affects earnings.

The method used to estimate damage costs caused by mercury to IQ decrements was first developed by Spadaro and Rabl, (2008). To estimate a worldwide average cost of damage per kg of mercury emitted due to ingestion, the method links statistics on country specific population and birth rates (i.e. the fraction of the population affected), to the slope factor and cost of IQ decrement (see Spadaro and Rabl, (2008) for more information). The US costs based on the IQ decrement is adjusted by transferring the country specific cost to other countries using the Gross Domestic Product (GDP) per capita expressed as Purchasing Power Parity (PPP) as a weighting factor. The total cost of damages related to welfare parameters of changes in development impairment have been reviewed in the DROPS project (DROPS, 2008). This cost includes those related to loss of earnings, loss of education, as well as the opportunity cost while at school (Scasny et al., 2008).

1.4 Economic benefits from reduced damage costs in 2020

1.4.1 Economic benefits from avoided IQ decrements

Economic benefits are estimated as the difference between the costs of damages determined for the 2005 emission situation and the costs of damages determined for the reduced emission levels estimated under the Baseline 2020 and MFTR 2020 scenarios. In this way, the societal benefits in monetary terms resulting from the employment of abatement measures needed to obtain the targets of emission reductions defined in the EXEC and MFTR scenarios are separately estimated. The results of these estimates are presented in Figure 16 (Sundseth et al., 2010).

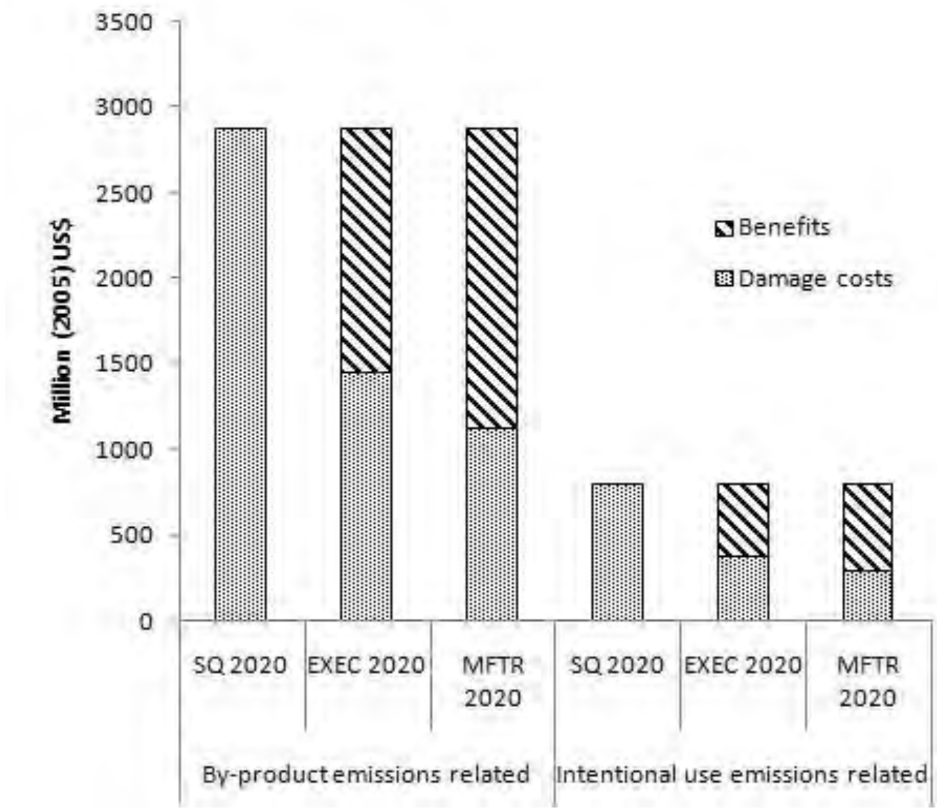

Figure 16 Comparison of damage costs and benefits within the 2020 emission scenarios for primary (by- product) and secondary (intentional use) anthropogenic emissions (Source: Sundseth et al., 2010).

In comparison with the costs in Figure 16 indicates that introduction of emission measures in the period between 2005 and 2020 to obtain the emission reduction targets defined in the 2020 EXEC scenario would facilitate decreased societal costs by about a factor of two. The damage cost reduction for the MFTR scenario is by a factor of 2.5. In addition to these benefits, significant co-benefits from the emission control for mercury are expected since control technologies used to reach the emission levels stipulated in the reduction scenarios are almost all multi-pollutant emission reduction technologies.

For the intentional uses of mercury, the most relevant comparison is between different end-use categories. This is mainly because there are large differences between different end-use categories as well as the difficulties in estimating the regional link between end-use of a product and the associated emission.

The EXEC scenario reduces the societal damage costs by more than half, thereby inducing societal benefits of more than US$1.8 billion in total. By implementing the MFTR scenario, additional benefits of US$0.4 billion would be reached in total.

1.5 Costs and feasibility of mercury emission reductions

Costs and benefits associated with mercury emission reductions from major anthropogenic sources were assessed by the candidate in UNEP, (2008b) and in Pacyna et al., (2010b). It was concluded that measures that include the application of technology, such as technology to remove mercury from flue gases in electric power plants, waste incinerators, and smelters, are rather expensive compared to non-technological measures such as prevention activity and promotion of mercury-containing waste separation. However, some technologies can be relatively inexpensive when used as an incremental approach with other pollutant-reduction measures.

At present, it is uncommon to invest in technologies that reduce only mercury from the emissions stream. Instead, a multi-pollutant approach is commonly used, which is much more cost effective. For example, approaches and technologies for controlling conventional air pollutants, including PM, SO_2, and NO_X, typically result in some reduction of mercury emissions as a co-benefit. In most cases, mercury controls are contingent upon controls for conventional pollutants, although the degree of the mercury capture by various technologies varies widely. In this context, the incremental cost of adding a mercury reduction effort to a certain strategy is much smaller. An overview of annual investment and operational costs of various emission control technologies in various industrial sectors was presented in Pacyna et al., (2010b).

Efficient, non-technological measures and pre-treatment methods are also available for the reduction of mercury releases from various uses of products containing mercury. These measures include bans on use and substitution of products containing mercury as well as cleaning of raw materials before their use (e.g., coal cleaning). These measures also include energy conservation options, such as energy taxes, consumer information, energy management, and improvement of efficiency of energy production through a co-generation of electricity and heat in coal-fired power plants. Other potential measures affecting mercury emissions also comprise prevention options aimed at reducing mercury in wastes, material separation, labeling of mercury containing products, and input taxes on the use of mercury in products.

For coal fired power plants, a primary control measure is to reduce the amount of mercury in the fuel for example 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. An overview of the air pollution controls and their mercury removal efficiencies are presented below.

Table 2 Example of air pollution controls and their efficiency (%) to capture mercury in coal fired power plants.

PM Controls	**Bituminous coal***	**Sub-bituminous coal***	**Lignite***
CS-ESP	0-63	0-18	0-2
HS-ESP	0-48	0-27	-¤
FF	84-93	53-67	-
PM and SO_2 control			
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		
NOx, PM and SO_2 control			
SCR + spray dryer + FF	94-99	0-47	0-96

Figure adapted from Sloss (2008). PM=particulate matter, SO2= sulphur dioxide, NOx= nitrogen oxides.CS - Cold Side; HS - Hot Side; ESP - Electrostatic precipitators, FF - Fabric filters, FGD - Flue Gas Desulphurization, SCR - Selective Catalytic Reduction.
**The ranges are based on a limited set of tests conducted at facilities in the USA.*
¤ *- no data*

Pre-combustion addition of halogens (e.g. bromine) has the potential to improve mercury removal by enhancing oxidation of mercury in the flue gas and thus increasing the removal efficiency in downstream particulate matter control and flue gas desulphurization equipment. Activated Carbon Injection, when used at commercial scale in conjunction with a particle control device, e.g., ESP or fabric filter can produce significant reduction of mercury emissions. Reductions of 99 % have been seen. Chemically treated carbons (e.g., brominated carbons) are more effective than conventional, untreated activated carbon when treating flue gases containing higher amounts of elemental mercury vapor.

One important aspect when estimating costs for mercury emission control are the existing conditions in a specific plant. The costs for mercury removal will be very different if the existing conditions involve power plants equipped with modern air pollution control than if very simple emission controls are installed. Optimization of existing emission control installations can potentially reduce emissions of mercury.

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 UNEP Open Ended Working Group (OEWG 1) that met in Bangkok in November, 2007 was carried out by the candidate together with other members of the NILU team. The main results of the report were peer reviewed in Pacyna et al., (2010b). A summary of the qualitative costs and benefits for each of the strategic objectives are presented in Table 3 below:

Table 3 Qualitative costs and benefits of mercury emission reduction for various industrial emission reduction options.

Reduction option		Costs	Benefits
1	Reduction from coal usage	Medium →Large	Large
2	Reduction from industrial processes	Medium → Large	Medium → Large
3	Reduction from waste	Small → Large	Large
4	Reduction from chlor-alkali industry	Small → Large	Medium → Large

In general, the costs and benefits vary significantly between strategic objectives. The report concluded, however, that there are potentially large benefits from investing in reducing global mercury emissions and exposure.

2 Justification for the topic

Energy and material demands in various production-and consumption systems worldwide are increasing as the global population and economy (GDP per capita) continues to expand. This causes generation of increased emissions associated with extractions of energy carriers and raw materials, as well as associated with the life cycles (production, manufacturing, use and waste handling) of the increasingly traded and consumed products. This in turn, raises concern among consumers and legislators on how human welfare is affected from the negative externalities on the environment and human health. Even though much progress has been made with regard to environmental and human health protection in various European countries, and emissions of certain substances (e.g. greenhouse gas emissions) have been reduced from the implementation of new abatement technologies and increased energy efficiencies, legislative instruments on various scales are necessary to help securing human welfare for future generations. For some pollutants, global action is required because of their long residence time in the atmosphere and thus the capability of being transported by air masses over the globe and deposited far away from the emission regions.

NILU- Norwegian Institute for Air Research, CEE (Center for Ecology and Economics) has been involved in developing emission inventories of emissions of metals (e.g. As, Cd, Cr, Cu, Hg, Mn, Pb, Sb, Se, V, Zn) contained as trace elements or contaminants in fuels or raw materials, and consequently discharged to air, water and land during the industrial transformation of these materials (see e.g. Pacyna et al., 2009). Important initial findings in these works are as follows:

- Anthropogenic emissions have become larger than the emissions from natural sources for the most of the above mentioned contaminants.
- Emissions to the atmosphere are at least equally important as the discharges to land and waters for many of the above mentioned contaminants.
- Environmental discharges of contaminants to various compartments of the environment are decreasing in Europe and the North America as production shifts and the environmental performance of the remaining production processes improves (Pacyna et al, 2009), but increasing in Asia, Africa and South America resulting in an increase of contaminants on a global scale.
- Mercury is today one of the most important contaminant due to its toxicity, global character and proven impacts on human health.

Important limitations to the research conducted can be defined as follows:

- Knowledge on emissions of contaminants on large geographic scale is limited due to inaccurate information on emission factors/rates for various industrial processes.

- Emission data have not always been connected to economic statistics.
- Environmental implications of emissions are for the contamination of various environmental media poorly understood as multi-compartment fate and risk models are generally lacking.
- There is an increasing interest in methods linked to material- and substance flow analysis, and development of emission factors and product life cycles.
- There is a lack of European models that link concentrations in raw materials, substance flows, impact assessment and damage cost assessment to decision making tools.
- Information on the most cost- effective measures in terms of reducing potentially adverse effects is missing in a European and global perspective.

2.1 The need for a new framework

Identification of efficient and suitable substance control strategies and implementation of cost-efficient abatement strategies critically depends on the quality of a decision support system that can be used to help authorities to identify current and future environmental problems and to reduce these problems by providing a holistic management approach. The decision support system relies on several questions that need to be answered:

- What are the main source categories, flows and environmental endpoints of contaminants and what are the production systems and consumption structures in the society causing these flows?
- What are the current and future environmental problems and how can they be reduced in the most effective way?
- What are the efficiencies and economic costs of emission control and how do the benefits from implementation of these measures compare to their costs?
- How can resources be allocated towards social optimality and how can criteria for taking action towards human welfare be established?

Human welfare critically depends on policy decisions to be based on concerns towards sustainable development. Sustainable development of various sectors of the economy was in the report "Our Common Future" by the World Commission on Environment and Development (WCED) related to the "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). Decoupling the links between economic growth and environmental degradation seems to be one of the key challenges[3], and it can further be claimed that human welfare is best served by improving the quality and flow of desired goods and services delivered rather than merely increasing the total money flow or production quantities. If high standards of human welfare are to be maintained, the concerns for a healthy environment must be balanced against requirements for economic growth. But, since any negative external effect will have implications for human welfare, it is important to consider actions to reduce these negative external effects. It is thus evident that human welfare depends on concerns towards a combination of both the economic/social system, the technical production system, and the natural system. Figure 17 illustrates combination of the three systems representing environmental system analysis.

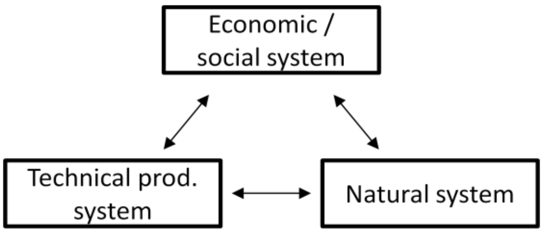

Figure 17 Three systems representing environmental system analysis (based on figure 1.5 in Baumann and Tillmann, 2004).

The essence of a system analysis approach lies within the analysis of existing problems and the identification of the most critical sources, in setting pollution control objectives and in the development of effective strategies to meet these objectives. The system analysis approach offers important practical advantages of high cost- effectiveness and an integrative decision making. It creates however, particularly demanding analysis requirements, which have to be simplified and addressed through special tools and procedures, if it is to be practical and widely used (WHO, 1993). To examine problems from such multiple perspectives, it calls for principles found in the field of *Industrial Ecology (IE)*, leading to systems thinking across sectors and product chains. Through *life cycle thinking*, considerations are being made on environmental impacts of production systems with the attention to raw materials used, supply chains, product use, and waste handling. It is a part of an assessment methodology that has been given increasingly attention by the European Commission in the recent years[4].

[3] See e.g. the work of the International Panel for Sustainable Resource Management (http://www.unep.fr/scp/rpanel/). (Accessed: January, 2010).

[4] The European Commission"s Joint Research Centre has provided technical guidance documents and a handbook on their International Reference Life Cycle Assessment Data System (ILCD), developed to support business and public authorities towards sustainable production and consumption (See http://lct.jrc.ec.europa.eu/index_jrc).

2.2 Why is there a need for a new framework for controlling mercury emissions?

As presented in the "*State of the art*" chapter, is mercury a matter of international concern. A legally-binding global agreement to reduce emissions of mercury is soon in place, meaning that many countries need to take steps (or are already taking steps) to lower their emissions. Identification and assessment of policy options that already are in place as well as setting pollution control objectives and in the development of effective strategies to meet these objectives are depending on a decision support tool that allow for identifying current and future environmental problems and to reduce these problems by providing a holistic management approach.

Recent scientific advancement in the field of mercury allows for more relevant information, accurate assessments and reduced uncertainty as well as a more complete picture of the problem and solutions to the problems. Such information is of outmost interest when it comes to justifying spending resources on relevant measures. To make sure that resource allocation is favoring human welfare, the economic costs of introducing these measures need to be compared to the economic benefits.

2.3 Major hypothesis:

The main hypothesis of this work is that there is enough information available, in the literature and primary from the candidate works, that a decision support tool needed for introduction of cost – effective abatement for mercury can be developed.

The main hypothesis consists of the following sub- hypothesis:

Sub- hypothesis 1. We are in the state that we can provide policy makers a decision support tool that would allow for cost- effective solutions.

Sub- hypothesis 2. It is possible to assess economic benefits and compare these to costs of introducing the relevant measures.

3 Major goal, objectives and tasks

The major goal of this thesis is to provide a novel combination of assessment tools that form a framework for a decision support system towards environmental policy on mercury in Europe. The decision support tool will act as a guideline for policy makers for the purpose of introducing strategies for cost- effective abatement of mercury.

The work proposed here is integrative. Already existing knowledge and methods are organized and linked to a set of tools in order to carry out the associated analysis of economic viable reductions of mercury emissions. To demonstrate the framework, a novel combination of analytical tools that will help policy makers identify current and future environmental problems of mercury contamination and take decisions on how to reduce these problems by contribution to a proper selection of measures will be demonstrated for the European Union (EU-27). The above mentioned goal will be obtained through the following tasks:

1) Identification of major EU-27 mercury emissions, main flows, and their environmental endpoints as well as the main production systems and consumption structures in the European society causing these flows.

2) Identification of relevant environmental and health endpoints and their dose- response relationships from exposure of mercury and methyl mercury.

3) Application of valuation methods to estimate economic cost of damages caused by mercury pollution.

4) Identification of relevant abatement options, their abatement efficiencies and economic costs.

5) Comparison the economic costs and benefits of introducing various mercury emission reduction measures in Europe.

6) Integration of the modules to a combination of analytical tools that form a framework for decision support towards environmental policy on mercury in Europe.

The tasks form an environmental system assessment tool presented in Figure 18. The assessment tool will provide a bottom – up method to calculate net benefits of a policy compared to scenarios that will be developed in this work. Cost assessment (i.e. investment and operational cost) and benefits assessment (i.e. avoiding damage costs) will give a basis for choosing between various measures. This in turn, is expected to provide a platform for verification of existing environmental policies and justification for new policies at various scales with respect to reduced negative externalities on human health and natural ecosystems. The work will benefit from results from previous research carried out by the candidate together with other members of the NILU team within the following programs and research projects:

I. United Nations Environmental Programme (UNEP) under the following topics:
   a. Global atmospheric mercury assessment: Sources, emissions and transport (UNEP, 2008a).
   b. An assessment of costs and benefits associated with mercury emission reductions from major anthropogenic sources (UNEP, 2008b).
   c. Study on mercury- emitting sources, including emission trends and costs and effectiveness of alternative control measures, the “UNEP Paragraph 29 study” (UNEP, 2010).

II. The Nordic Council of Ministers study on socio- economic costs of continuing the status quo of mercury pollution (NCM, 2008).

III. Projects with funding from the European Commission:
   a. Development of macro and sectoral economic models aiming to evaluate the role of public health externalities on society (EU DROPS).
   b. Source control of priority substances in Europe (EU SOCOPSE).
   c. Health and environment integrated methodology and toolbox for scenario assessment (EU HEIMTSA).

IV. AMAP (Arctic Monitoring and Assessment Programme) on mercury in the Arctic (e.g. AMAP, 2011).

During these projects, the candidate has obtained:

- A good knowledge of the EU legislation and policy regarding mercury emissions, its implementation and relation to relevant international policies;
- Familiarity with impact assessment methods used by the Commission and with the political context in which the Commission operates;
- Knowledge and experience of EU, UNEP, and UNECE policy development and decision making;
- Expertise in the preparation of data inventories and their verification;
- Expertise in industrial pollution abatement techniques and associated costs and in undertaking assessments of the macroeconomic impacts of industrial pollution policies and their cost effectiveness.

Based on knowledge and experience obtained from the previous works, this thesis aims to contribute to a systems perspective in the fields of environmental science that is necessary for improved decision making on an EU- level regarding mercury pollution. The study contributes substantially to the improvement of the completeness and accuracy of information needed for impact assessment, cost assessment and development of substance flow analysis (SFA) diagrams in EU. The structural approach that forms a framework for decision support as an *environmental system assessment tool* is illustrated in Figure 18.

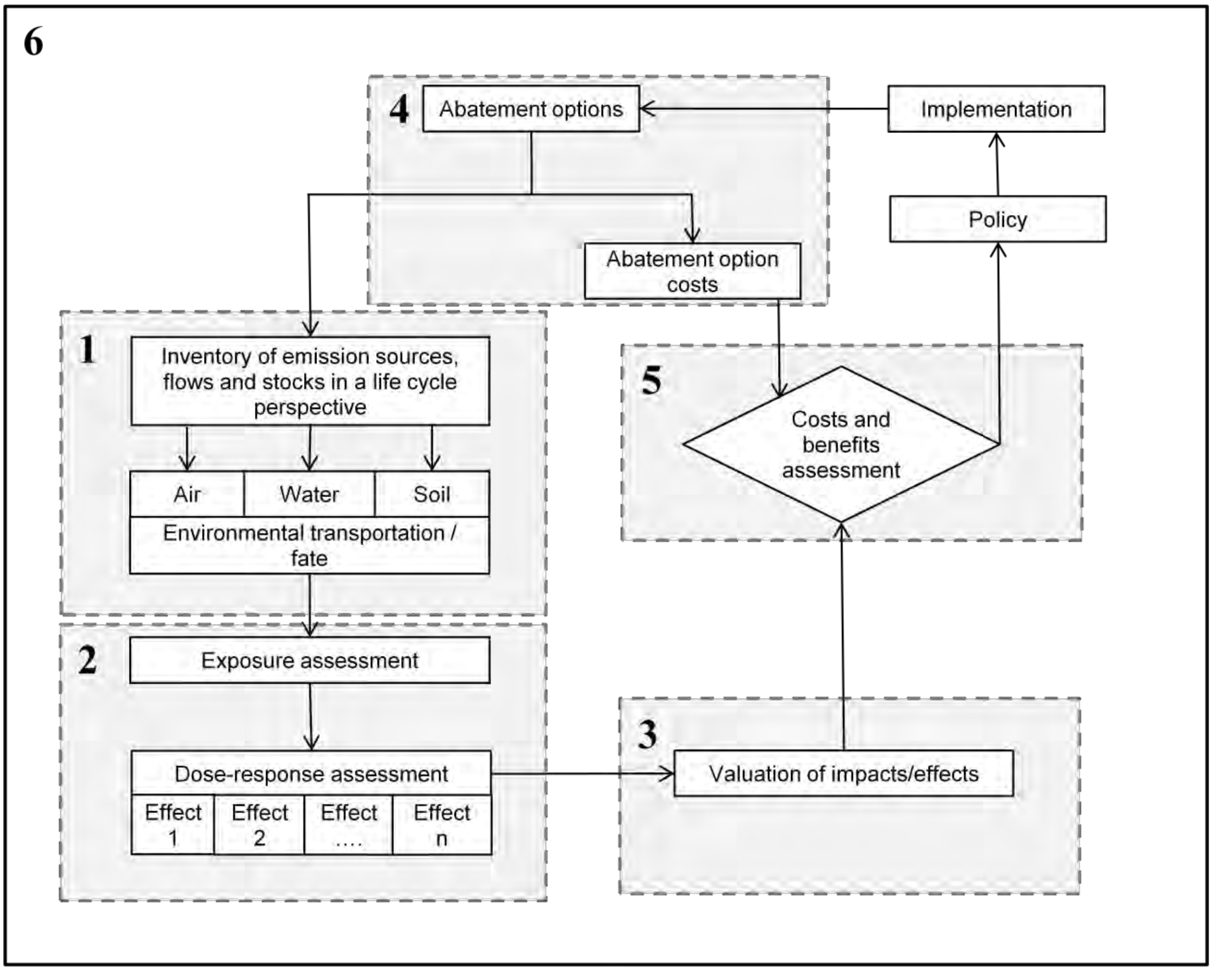

Figure 18 Structural approach that forms a framework for decision support (Modified model initially based on Global Atmospheric Pollution Forum, (2008)).

The decision support system should provide a format in which information, needed to prepare and to take decisions, can be gathered, stored, updated and evaluated. The tool is first and foremost supposed to support decision makers at national or European level, but can with modifications also be used for decision making at a local level.

3.1 Novelty

The innovative nature of this work should be defined as follows:

- *Update on mercury emission inventory for the EU 27 region and description of main mercury substance flows in the EU 27*. By compiling existing information and filling data gaps -a more complete description of mercury emissions and flows are provided. The substance flow analysis will provide new and innovative information, and will also allow for a deeper assessment of potential measures.

- *Identification and evaluation current and future technological and non- technological mercury abatement measures using cost- benefit methodology*. The work will provide stakeholders (e.g. industry, authorities, and NGOs) with relevant information.
- *Development and application of a decision support tool for management of mercury*. A decision support tool for management of mercury is a new and innovative product which will have a practical value for industries and authorities when implementing the globally legal instrument on reducing mercury.
- *Development of an innovative structure for involving stakeholders and bridging the gap between science, policy making and the people*. The aim is to make the results of this work useful, relevant and applicable to the mercury emission reduction process and to form consensus around the decisions and priority setting involved in this process.

By recommending the system analysis approach, this work enables a novel, holistic approach to the management of air, water, and soil pollution problems and the identification of the most important point sources and flows, to assess the impacts of the released loads into the receivers, setting definite pollution control objectives and in the development of effective strategies to meet those objectives.

The method approaches interdisciplinary including emission estimation, technology assessment, dispersion modeling, impact estimation and (socio-) economic evaluation. It provides information on; (i) how control measures affect the emissions, (ii) how the exposure of humans and the environment changes under various control scenarios, (iii) what are the economic values (benefits) of the changes, and (iv) how do these benefits compare to the cost of measures. This work thus contains all the information required to analyze the current situation and to develop cost- effective management approaches on mercury.

The candidate has carried out together with other members of the NILU team the following novel works on the subject of mercury:

- The global mercury inventory (UNEP, 2008a) published in Atmospheric Environment (Pacyna et al., 2010a) which is the first of its kind, showing the 2005 atmospheric emissions of mercury from primary anthropogenic sources in 230 countries, emission trends (from 1990-2005) of these emissions and at the same time forecasting future emissions until 2020 on the basis of emission scenarios. In the same study, maps of atmospheric mercury emissions from anthropogenic activities, taking into account the chemical forms of mercury emitted from European point sources were developed.

- An assessment of (i) qualitative costs and benefits associated with emission reduction measures from major anthropogenic sources, (ii) the study on socio- economic costs of continuing the status quo of mercury pollution globally, as well as (iii) costs and effectiveness of alternative control measures; -were based on the novel works presented in the above mentioned study.
- The simplified EU-27 SFA map on mercury performed in the EU SOCOPSE project (Sundseth, 2009) is the first of its kind, illustrating the 2005 emissions, flows and environmental endpoints of mercury originating from European anthropogenic sources. It included the first attempt at describing its major sources, pathways, and release of mercury into the natural compartments; atmosphere, water and land with the purpose of providing necessary information to a decision support system for implementing the Water Framework Directive (WFD).

EXPERIMENTAL PART

4 Description of methodologies

4.1 The decision support system

The structure of the proposed decision support system on reducing mercury emissions in the EU is based on a decision support system handbook that was developed by the candidate during the EU SOCOPSE project (Baartmans et al., 2008) and that is further improved in his research. It reflects a general structure that is presently applied in the EC program REACH (2008) and it also compromises information from various other guidelines, such as AEA, (1999) and the IPPC Reference document EC, (2006). The decision support system developed in this thesis thus facilitates a systematic and comprehensive assessment of the relevant costs and benefits of continuing the baseline scenario of mercury pollution compared to the conditions of possible emission restrictions. It is iterative in each step, meaning that data and assessments are constantly improved and uncertainties reduced as it is being applied.

The techniques described in this work, can be applied both on local, national, and regional level. Although the decision support tool is developed for the control of mercury, it can with certain modifications also be applied for other priority substances.

The following subchapters describe the general structure of the decision support system and subsequently each step of the decision support system in more detail. An overview of these steps is described in Figure 19 below.

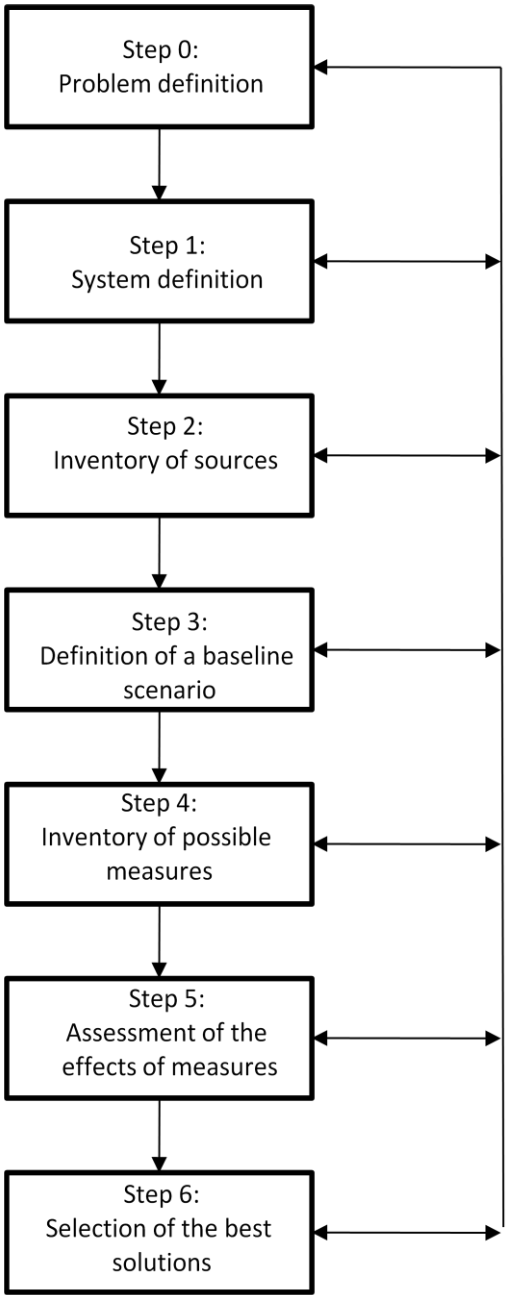

Figure 19 Overview of the decision support system.

The above framework starts with defining the problem and setting the goal of the assessment. Thereafter, it seeks and analyzes relevant information as well as outlines the available alternative solutions. It ends wilt calculating their relative merits, making and implementing a decision, and evaluating outcomes as well as making modifications according to the best solution.

4.1.1 Step 0 – Problem definition

In step 0, the problem definition for mercury is evaluated. It thus sets the aim of the assessment. The result of this step is an overview of existing legislations, directives or other commitments towards mercury emission reductions as well reasoning of the required emission reductions.

4.1.2 Step 1 – System definition

In step 1, the boundaries of the studied system are set, meaning that the geographical, temporal, physical, and societal characteristics of the system are decided upon. These characteristics may however, be adjusted when the impacts are analyzed in more detail in the next steps.

4.1.2.1 Geographical boundary

Often, the geographical boundary within a study is limited to the politically defined and administrative regions since information typically is collected on these levels. Such geographical boundaries, however, open for more efficient introduction of measures as they typically exist within the same defined boundaries as the political and administrative stakeholders. When setting the geographical boundaries, it is important to keep in mind that all impacts (i.e. human health, environmental, economic and social) of the studied system should be included independently of where they occur. It should therefore be clearly stated where any impact occur outside the EU region.

4.1.2.2 Temporal boundary

As existing data and statistics often are annually collected and reported, the temporal boundary typically reflects the period of one year. In setting the temporal boundaries, it is also important to make sure that all relevant impacts are included regardless of when they appear in time. Since the „baseline" or the „proposed restriction" scenarios may involve significant changes in trends in emissions or use of mercury (e.g. from introduction of legislation, development and introduction of technologies) that may include different time derogations for different source categories, industrial actors or consumers. In some cases this calls for selection of a cumulative assessment period. Often impacts occur at a much later stage, e.g. as for mercury released to and transported in the marine environment. A trend analysis and qualitative assessments of these impacts may be necessary.

4.1.2.3 Physical boundary

The physical boundaries undertake all the emission sources / processes[5] and mercury- containing product value chains in the investigated system relevant to the emissions and flows of mercury. Actions towards emission reductions reasoned in step 0 can affect the system both upstream (i.e. material extraction, suppliers etc.) and downstream (use and waste management) from both the uses of raw materials containing mercury and the intentional use of mercury. A general SFA/MFA diagram illustrating substance and/or material flows throughout the entire value chain (i.e. from geological storage, through production, manufacturing, use, waste (and recycling/remanufacturing/reuse loops)) is presented in Figure 20 below.

[5] A process is defined as the transformation, transport, or storage of materials.

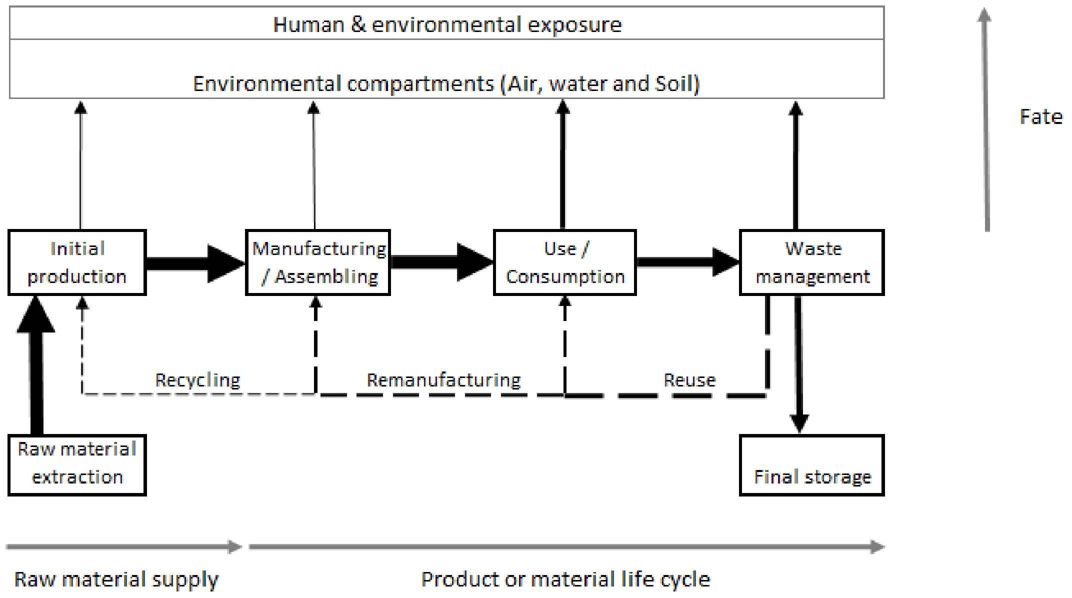

Figure 20 A general SFA/MFA diagram illustrating material and/or substance flows throughout the entire supply chain.

4.1.2.4 Stakeholder involvement

Actions towards emission reductions can directly affect industry and users. Key stakeholders should therefore be identified at this stage. Stakeholder involvement reduces the risk of a policy not being carried out as planned and they may also contribute with knowledge and information needed in the assessment. Three groups of stakeholders can be defined:

- Organizations and people that have a direct impact on environmental quality management or are directly affected by the relevant policies (e.g. regulators on the local, regional, national and international level, industries and consumers).
- Organizations and people that have an impact on relevant decision making (e.g. NGOs, scientists, citizens and insurance companies).
- Those who have an indirect impact on or are indirectly affected by implementation of policy (e.g. other users of natural resources).

A more detailed analysis of stakeholder involvement and how to perform a stakeholder analysis is more closely described in the SOCOPSE DSS Handbook (Baartmans et al., 2008).

4.1.3 Step 2 – Inventory of emission sources

The step involves an inventory of emission- sources which eventually affects the environmental concentrations. The inventory phase should contain data collection for all relevant source categories emitting or consuming mercury according to the system boundaries decided upon in the problem and system definition (step 0 and step 1). Emissions and flows should be calculated, resulting in the construction of a substance flow diagram. A scheme of step 2 is illustrated below:

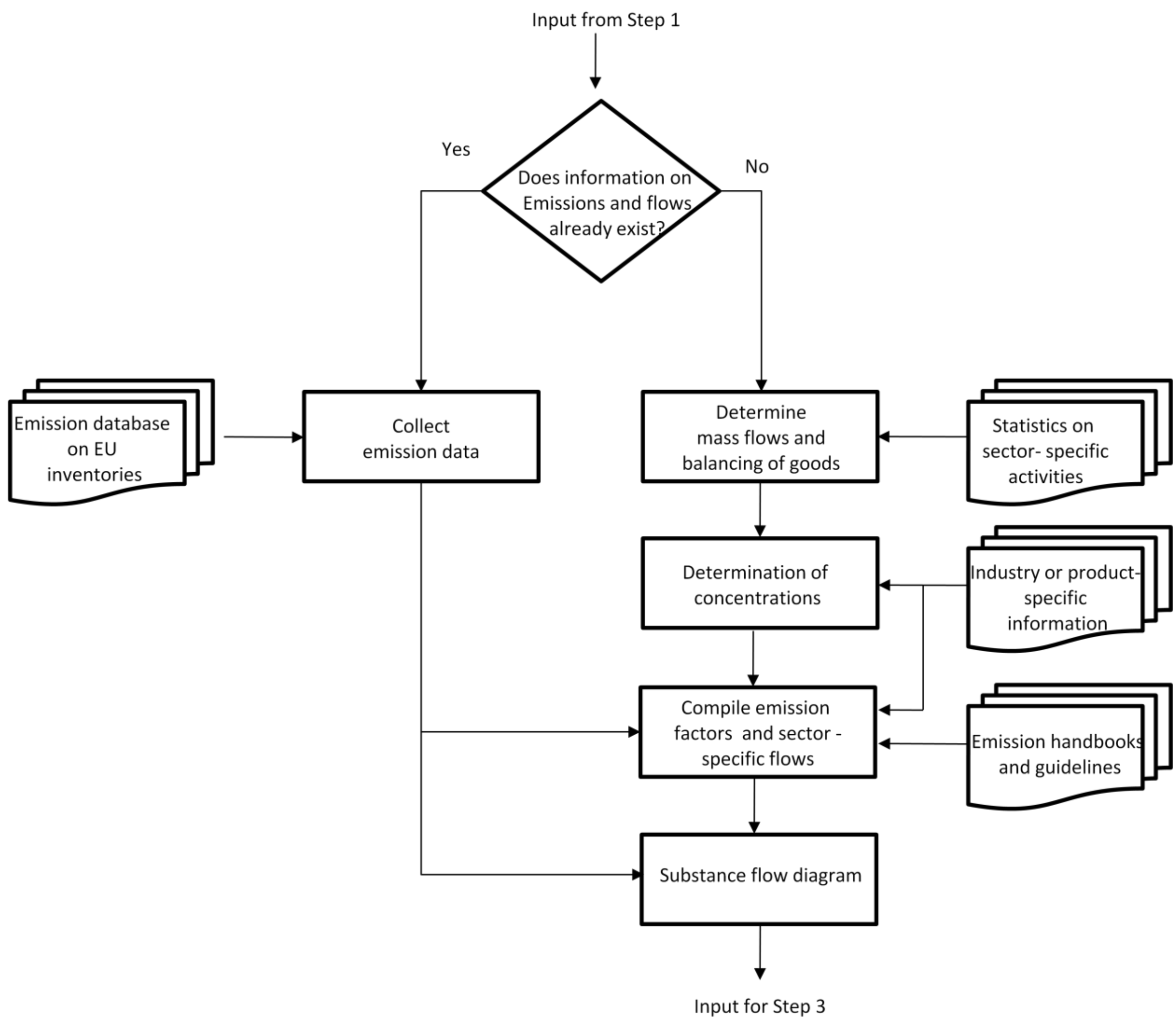

Figure 21 Step 2: Inventory of sources scheme.

4.1.3.1 Data collection and determination of mass flows

Since mercury is emitted from various anthropogenic sources, either as a primary anthropogenic emission source from entering high temperature industrial processes as a minor constituent in fuels, raw materials and wastes, or from the entire life cycle (i.e. mining, production, manufacturing, storage, use and disposal) of its large range of applications, data needs to be collected and/or estimated from a variety of information sources.

A simple SFA diagram illustrating the main emission and flows of mercury can be prepared from information on;

1. emissions to the atmosphere, water and land as available from the literature, research reports, national authorities, international organizations and programs, and national and international emission data collection sources, and/or from,

2. a mass balance approach based on information on; i) mercury content and other compositional characteristics of fuels, raw materials, technical configuration of the source facility and existing emission control installations or, ii) mercury content in products combined with main pathway distribution factors.

The latter obtained information should then be combined with trade, activity or consumption data as well as appropriate emission factors, and release rates available from national and international statistical yearbooks and guidelines. This step should also be used as verification of available data collected from national authorities etc. In general, the data should be as complete as possible to account for all the emissions, raw material inputs and outputs. The emission factors assume a linear relation between the intensity of the activity and the emission resulting from this activity. For mercury emissions in Europe, the emission factors should first and foremost be based on information obtained from measurement of concentrations of mercury in the flue gas of selected plants and waste incineration plants in Europe, as well as from mass flow balances of mercury in power plants and other emission sources. An example on how emission factors are determined can be found in Box 1.

The approach for the primary anthropogenic emission source estimates to an environmental compartment can generally be described as equation (1) (Glodek and Pacyna, 2009).

(1) M Air, Water, Land=S*Ms*k

The mercury emitted to an environmental compartment (M Air, Water, Land) from various source categories relates to the compositional characteristics of fuels or minerals (Ms) multiplied with the consumption of fuels or minerals (S) in the actual sector, and the penetration coefficient (k) of mercury to the environmental compartment, in which (1-k) reflects the emission control efficiency coefficient of the emission control equipment installed. In equation (2), the environmental compartment- specific mercury emission factor (EmFAir, Water, Land) is represented by the (Ms) multiplied with (k):

(2) M Air, Water, Land=S*EmF Air, Water, Land

Emissions generated from the „intentionally use of mercury in products"- category can be estimated by linking information on consumption of various mercury- containing products (S) to the methodology described in (Kindbom and Munthe, 2007), i.e. using distribution factors (D) to allocate the mercury-containing products into different waste treatment categories and subsequent attribute to them atmospheric emission factors on breakage, metal scrap smelting, waste incineration and land-filling. (See Kindbom and Munthe, 2007 for complementary information). The methodology can be summarized in equation (3).

(3) M Air, water, Land=S*D*EmF Air, Water, Land

A Stock-Flow model approach (e.g. Muller , 2006), originally developed to simultaneously forecast resource demand (inputs) and waste generation (outputs), can be applied for developing future projections on emissions, discharges and releases from mercury used intentionally in products, whilst at the same time accounting for the mercury accumulated in society (i.e. in the use phase). The basic model assumptions are then driven by physical determinants, such as regulative changes or substitution effects which in turn, affect the demand of mercury embodied in products. This in turn, induces a push of emissions or waste over a certain lifetime whilst mercury stocks are accumulated and generated in the system. The Stock- Flow model is described in more detail in the Appendix.

Box 1 –Emission factors

Emission factors assume a linear relation between the intensity of activities and the emissions resulting from these activities. Determination of emission factors using a mass balance approach for power plants and other point sources (method described by Pacyna, 1980) has been based on the difference in amount of mercury introduced to the industrial facility together with the raw material (e.g. coal), and the amount of mercury leaving the process embodied in the product or along with the residues collected by the emission control installations. The emission factor for industrial sources, energy production and waste incineration are according to Pacyna, 2010c derived from the following equation:

$$EmF_{Air} = \frac{E_{Hg}}{M}$$

The emission factor (EmF_{Air}) equals mercury emissions to the environmental compartment (E_{Hg}) in relation to the raw materials used (M).

Example: Methodology for determination of emission factors for the case of a coal power plant.

For the case of a coal power plant, the emission factor can be derived from the following equation:

$$EmF_{Air} = \frac{XHg_w - (XHg_z + XHg_p)}{M_w}$$

Index of mercury emissions (g Hg /t coal)

XHg_w= amount of mercury in the coal (Hg / year)

XHg_z=amount of mercury in the slags (Hg /year)

XHg_p=amount of mercury in the fly ash (Hg /year)

M_w=amount of burned carbon (t/year)

Box 2 –Aggregated emission factors

A simple way of aggregating sector- specific emission factors under various assumptions on socioeconomic and technology development in countries or regions is to multiply an unabated emission factor multiplied with the mercury removal efficiency of certain measures used. The following formula was used in the EU EPREME project to estimate sector specific emission factors:

$$EF = \frac{\sum_{c \in C} UEF \cdot A_c \cdot (1 - \sum_{m \in M} E_m \cdot IG_m)}{\sum_{c \in C} A_c}$$

A_c Sector- specific activity in sector c.

C Set of all countries.

Em Sector- specific efficiency of measure m.

EF Sector- specific emission factor.

IGm Sector- specific degree of implementation of measure m.

M Set of all measures for the sector.

UEF Unabated emission factor.

The resulting emission factor for application of a certain measure m can for simplicity be presented as in the following formula:

$$EF_m = UEF \cdot E_m$$

To estimate emissions, the sector- specific emission factor is multiplied with the implement degree of certain measures with a sector specific Hg removal efficiency.

4.1.4 Step 3: Definition of the baseline scenario

Step 3 seeks to answer whether additional measures are necessary to reduce emissions, and to investigate if there are reasons to assume that the present situation will change in the future. Step 3 thus results in a SFA diagram with future emissions and flows and their possible sources. The baseline scenario considers any relevant legislations/directives or modifications to these during the timescale undertaken in the analysis. Some emission sources may already or in the near future be eliminated by existing regulations/policies. The step can be used for identifying which will be the most important emission sources and at the same time identify unintentional cross- media effects of the baseline scenario.

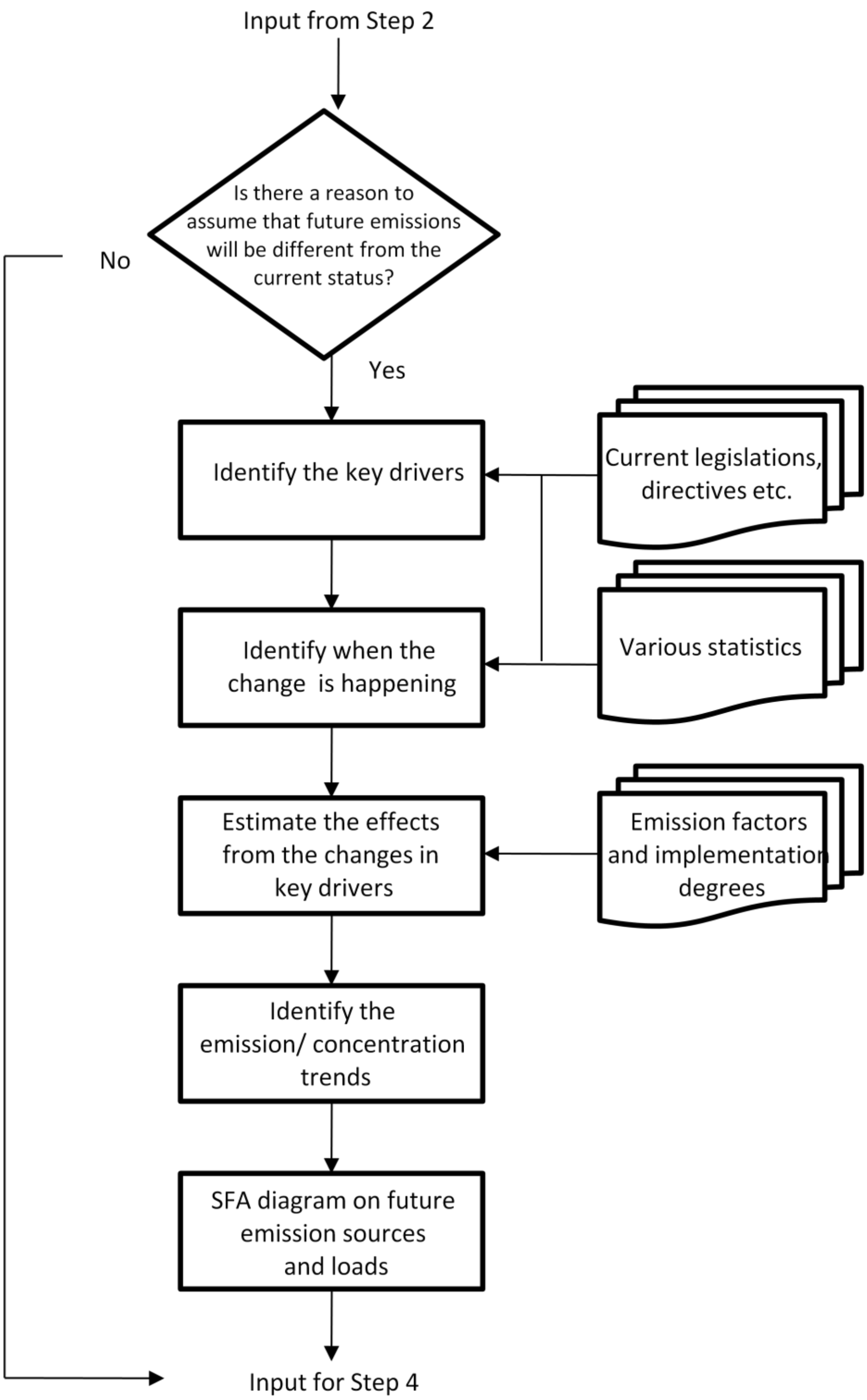

Figure 22 Step 3: Definition of the baseline scenario scheme.

4.1.4.1 Identification of key drivers

A key issue when it comes to quantification of future substance flows and emissions to the environment is to identify the future development of the main drivers of the system. Main drivers are typically introduction of legislations and directives, technology change, population increase or decrease, development of the economy, and consumption increases or decreases. In addition, various behavioral responses from the stakeholders who are affected by the legislations and directives can influence the implementation process.

4.1.4.2 Identify the effects from change in key drivers (including identifying when the change is happening)

In this sub- step the timeframe of the change in flows and emissions are identified for the analysis. Some strategies, regulations, directives, frameworks or conventions sets a certain year for fulfillment of their objectives while others need a certain period of time before being achieved. While some of the emission reduction options are already in place, -others can be implemented in the near or far future. The result of this sub- step is a table of existing technologies and implementation degrees as well as an overview of the relevant variables and their changes with time.

4.1.4.3 Environmental fate modeling

Anthropogenic activities influences natural cycling by altering the rate at which mercury is transported between environmental compartments. Natural emissions and re- emissions of deposited mercury from anthropogenic activities are not distinguishable and are normally treated as natural emissions. The biogeochemical cycle of mercury in the natural environment relates to physic- chemical and meteorological factors as well as surface characteristics, -leading to variable mercury fluxes. One can make use of environmental fate models, but transport processes of heavy metals such as mercury can be very complex and local specific. Specialists should be consulted to make judgments on this sub-step.

4.1.4.4 Emission/ concentration trends

The emission scenario is made by applying the predicted changes in the key drivers to the present situation. The data obtained are used in environmental fate models to predict the concentration levels and trends that can be expected in the chose time frame. Previous emission trends (and concentration measurements) are checked against the predicted changes as a result of the change of the key drivers.

4.1.5 Step 4 – Identification of possible measures /emission reductions

In step 4, possible additional measures and their emission removal efficiencies (including co- control of other substances) are identified. The result is a SFA scheme that illustrates likely future emissions based on assumptions on implement degrees of technical measures as well as other management options. The options include process- oriented options, end- of- pipe techniques, product substitution, as well as community level options (e.g. waste disposal, sediment or soil removal etc.).

On the basis of step 3, the necessity of introducing measures is located. The actual sector sources are checked against the measure options (database) which contain information on mercury removal or reduction efficiencies as well as investment and/or operational costs.

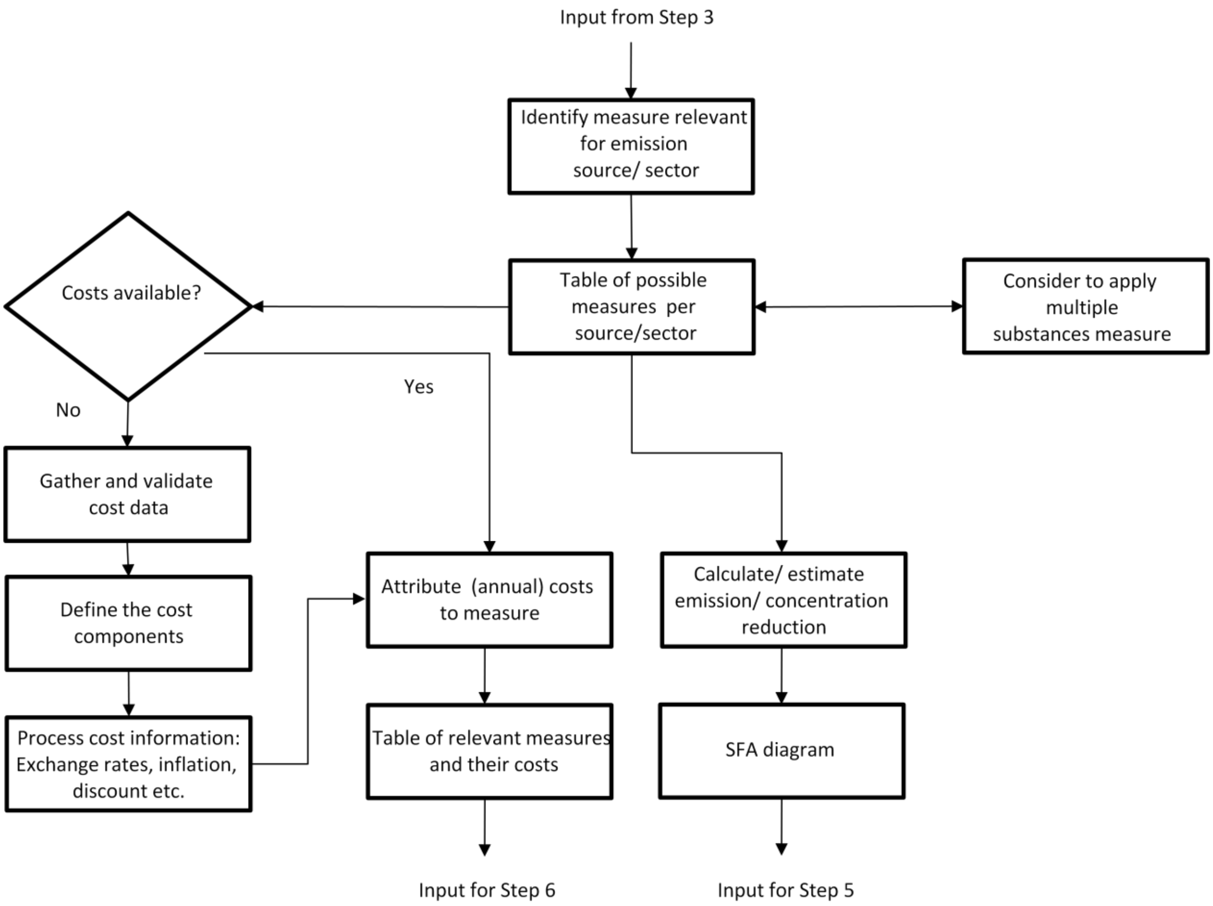

Figure 23 Inventory and effect from possible measures scheme

4.1.5.1 Identify possible measures

A table of possible measures per source category should be made. The measure and its efficiency should be identified as precisely as possible. Efficiencies of the measure are often expressed as a percentage of mercury captured or removed and is typically recorded by adding the removal efficiency to the unabated emission factor.

The alternative measures that might be assessed include:

- Process design, e.g. cleaner technology; changes or replacements to processes, or plants, or equipment; alternative synthesis routes; etc.
- Selection of raw materials, e.g. cleaner fuels, less contaminated raw materials, etc.
- Process control, e.g. process optimization, etc.
- Housekeeping- type measures, e.g. cleaning regimes, improved maintenance, etc.
- Non- technical measures, e.g. organizational changes, staff training, the introduction of environmental management systems, etc.
- End-of-pipe technology, e.g. incinerators, waste water treatment plants, adsorption, filter beds, membrane technology, etc.

Before selecting a possible measure, its economic costs and its ability of co- controlling other substances should be checked. Any other side- effects from the measure, such as effects on other pollutants and environmental media should be described and (as far as possible be) quantified.

For national or international policy analysis, the future scenario usually consists of specific types of measures applied to several sources in one (or more) sectors. The sector may have a mixture of existing measures already in place so that new measures that need to be replaced retrofitted to e.g. a specific plant. New emission estimates are estimated by modifying the emission factor.

4.1.5.2 Costs of measure

Cost data for installing, operating and maintaining a technique should be collected and processed consistently. In general, the data can be obtained from a variety of sources, including;

- Industry, e.g. construction plans, documentation of industrial projects, permit applications
- Technological suppliers,
- Authorities, e.g. the permitting process,
- Consultants,
- Research groups,
- Published information, e.g. reports, journals, websites, databases, conference proceedings,
- Cost estimates for comparable projects in other industries or sectors.

The costs should be expressed in relation to the existing situation, i.e. the situation where the additional measure has not been implemented. This means that costs are measured as additional costs to a baseline scenario. As a minimum, the total investment expenditures (often fixed costs) and total annual operating and maintenance costs (often variable costs) should be reported. Fixed costs are usually capital investment costs, while variable costs are typically costs that depend on the process throughput (e.g. electricity). These expenditures are commonly reported separately. To make these costs comparable to one another, either the fixed costs have to be reported in annual terms, or the net present value of the variable costs has to be calculated. Only direct costs should be taken into account.

Some measures explicit reduce mercury whilst others are originally designed to remove other pollutants. In the case of mercury specific measures, the entire costs should be attributed to mercury removal. In other cases, the aim of introducing the measure may be reducing other substances such as PM, NO_X, SO_2. This may open for attributing costs between the various pollutants. *If* the costs associated with an environmental protection measure have been apportioned between two or more controlled pollutants, the method of apportionment should be described.

The costs of environmental protection measures may need to be presented in such a way that various measures with different economic lives can be compared. This is accomplished by converting all the cash flows occurring over the life of a measure to an annual cost. It is important to keep in mind, however, that costs and prices are not fixed over time. E.g. the unit price of measure often falls as the measure are moving from an experimental measure to a series- produced measure. Also, efficiencies are often lower and maintenance costs often higher for aged measures. To account for future costs that may appear over a number of years, the present value has to be calculated. The present value is basically today‟s value of a future payment or series of future payments, discounted to reflect the time value of money (as well as investment risks). The discount rate should also be stated and explained.

Box 3 – Present value

The present value can be derived from the following formula:

$$Present\ value = \frac{cost_n}{(1+r)^n}$$

Cost = cost over n years

n – lifetime in years

r – the discount (interest) rate.

Discounting/interest rates facilitates comparison between costs (or benefits) occurring at a different point of time. Discount/interest rates are justified by 1) the opportunity cost of capital and 2) time preferences.

For costs that appear over a number of years, the present value can be derived from the following formula:

$$Present\ value = \sum_{t=0}^{n} \frac{cost_t}{(1+r)^t}$$

$Cost_t$ = cost in year t

t = year 0 to year n

Box 4 – Interest rate

The real interest rate can be derived from the following formula:

$$real\ interest\ rate = \left[\frac{(1 + nominal\ interest\ rate)}{(1 + inflation\ rate)}\right] - 1$$

Nominal market interest rates equal the sum of the real rate of interest (i.e. the rate of return in capital) and expectations on inflation.

Box 5 – Annual cost

The annual costs can be derived from the following two alternative approaches:

Alternative 1:

$$total\ annual\ costs = C_0 \left[\frac{r(1+r)^n}{(1+r)^n - 1}\right] + OC$$

C_0 – the cost at year 0.

N – the estimated economic lifetime of equipment in years

OC – the net operating and maintenance costs, constant for each year

Alternative 2:

$$total\ annual\ costs = \left[\sum_{t=0}^{n} \frac{(C_t + OC_t)}{(1+r)^t}\right]\left[\frac{r(1+r)^n}{(1+r)^n - 1}\right]$$

t=0 – the base year for the assessment

C_t – total investment expenditure in the period t

OC_t – the net operating and maintenance costs in period t

The latter approach gives more flexibility in terms of explicit accounting for real price changes of the operating and maintenance costs (AEA, 1999).

4.1.6 Step 5 – Assessment of the effects of the measures

In step 5 the effects of the measures identified in the previous step are assessed. Potential impacts are identified through data on emissions and exposures and on the related human health and environmental effects. The assessment of impacts should focus on the difference between the baseline scenario and the alternative scenario. In this way, the additional costs or savings compared to the baseline scenario are assessed. The impacts should as far as possible be described quantitatively where suitable data exists.

The results of the step, is a table of effects, costs and benefits compared to the baseline scenario.

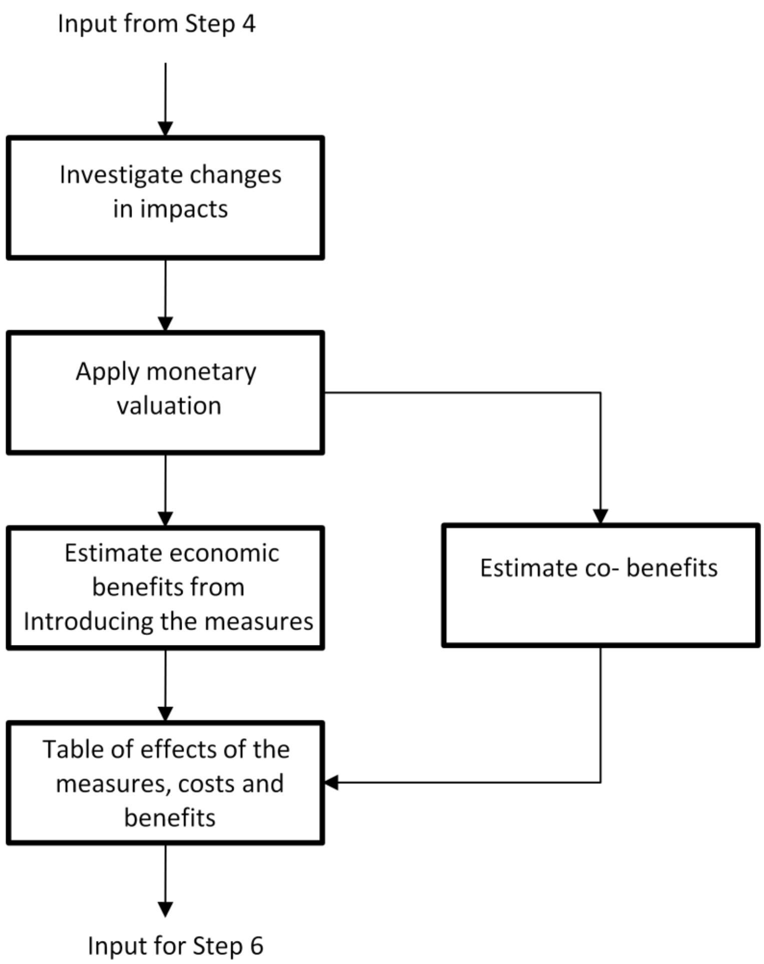

Figure 24 Assessment of the effects scheme.

4.1.6.1 Investigate impacts and estimate changes

Environmental fate models can be used to simulate the chemical`s transport, deposition and concentrations in the environment, and can be used to identify the importance of the changes in emissions on environmental concentrations.

Impacts from the different level of exposure should be defined by a dose- response relationship (function) to the magnitude of the substance.

4.1.6.2 Monetary valuation

Damages to human health – To estimate the monetary value of impacts on human health, methods such as health- adjusted life year (HALY), Disability- adjusted life year (DALY) or quality of life year (QUALY) is commonly applied. Other valuation- methods are based on value of statistical life (VSL[6]) or value of a life year (VOLY). Damages to health is basically covering the two main categories; - direct and indirect costs. Direct cost is based upon the cost-of-illness approach[7], meaning that the cost estimate take into account the incremental medical costs associated with medical diagnosis, treatment and follow-up care (as defined in US EPA, 2002). Valuation of indirect costs covers both loss of production and dis- welfare associated with the disease. For instance, loss of productivity is an indirect cost category that expresses the lost value of being absence from work because of the illness.

Box 6 – Value of statistical life

$$VSL = \sum_i \frac{WTP_i}{\Delta_s N}$$

N – population at risk

$$VSL = VOLY \sum_{i=a}^{T} (\frac{aP_i}{(1+r)^{i-a}}$$

aP_i – conditional probability to live until year i for a person at age a.

T – maximum of expected life time

[6] The main issue has been how to 'transfer' VOSLs taken from non- environmental contexts (e.g. immediate risks such as accidents) to environmental contexts.

[7] The term is sometimes used in the literature to cover both direct and indirect costs.

To estimate economic values on damages to ecosystems it is often necessary to quantify the value of ecosystem services since usually no market value can be (or difficult can be) obtained. Monetary valuation is basically an attempt to associate a currency unit to goods and services provided by the natural environment or damages to these. Since natural capital in most cases provides common goods and services, they are often left outside the markets sphere and they are thus not included in economic analyses.

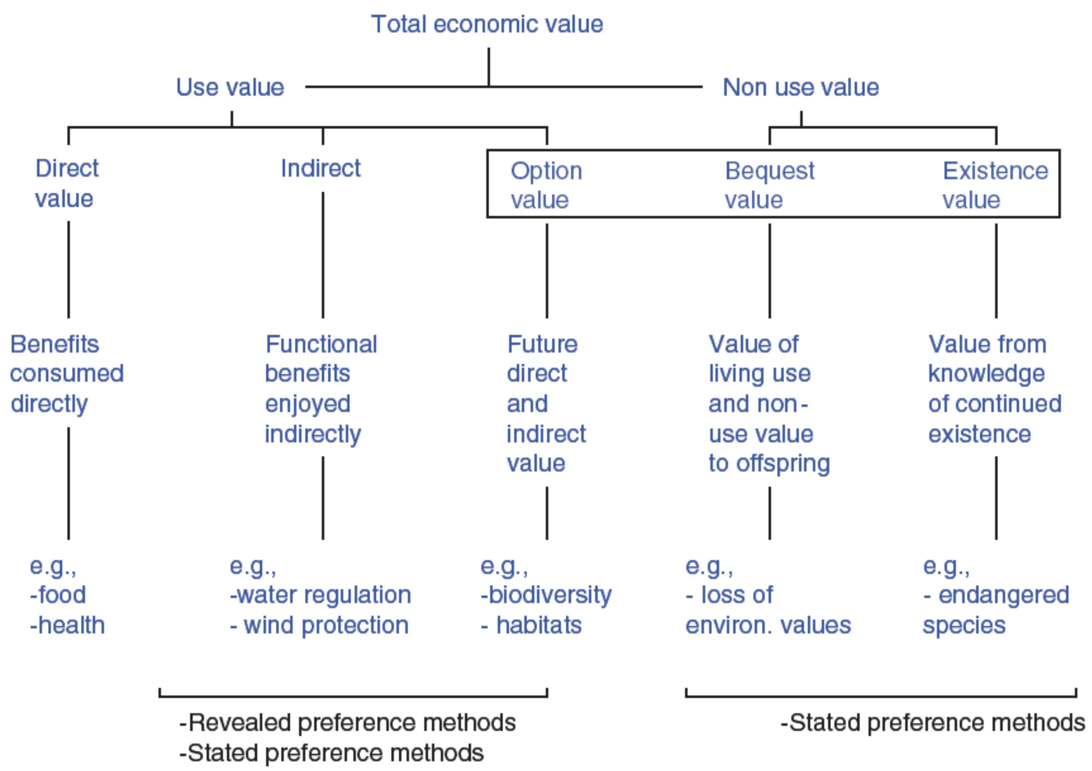

Figure 25 An overview of methods to estimate use and non use values.

The direct use value is the value attributed to direct utilization of ecosystem services and option value is the value that people place on having the option to enjoy something in the future, although they may not currently use it. On the other hand, the non-use values include both bequest and existence value. Bequest value is the value that people place on simply knowing that something exists, even if they will never see it or use it. When associating a currency unit to goods and services provided by the natural environment or their damage, there are three main groups of methods based on use values (direct and indirect) and non-use values:

1. Revealed preferences where the value of non-market goods and services can be reviled by observing the consumer`s behavior. Preferences can directly be observed by allowing for market prices or indirectly through hedonic techniques.

2. Stated preferences which either can be directly based on contingent valuation (hypothetical markets), or indirectly through choice experiments.

3. Market based methods elect peoples willingness to pay or willing to accept e.g. environmental damage.

4.1.7 Step 6 – Selection of the best solutions

Step 6 is on the basis of step 4 and 5 selecting the best sets of measures. A dialogue with stakeholders should be established for the selection process. To rank the measure options, cost and benefits associated with introducing the measure(s) should be compared.

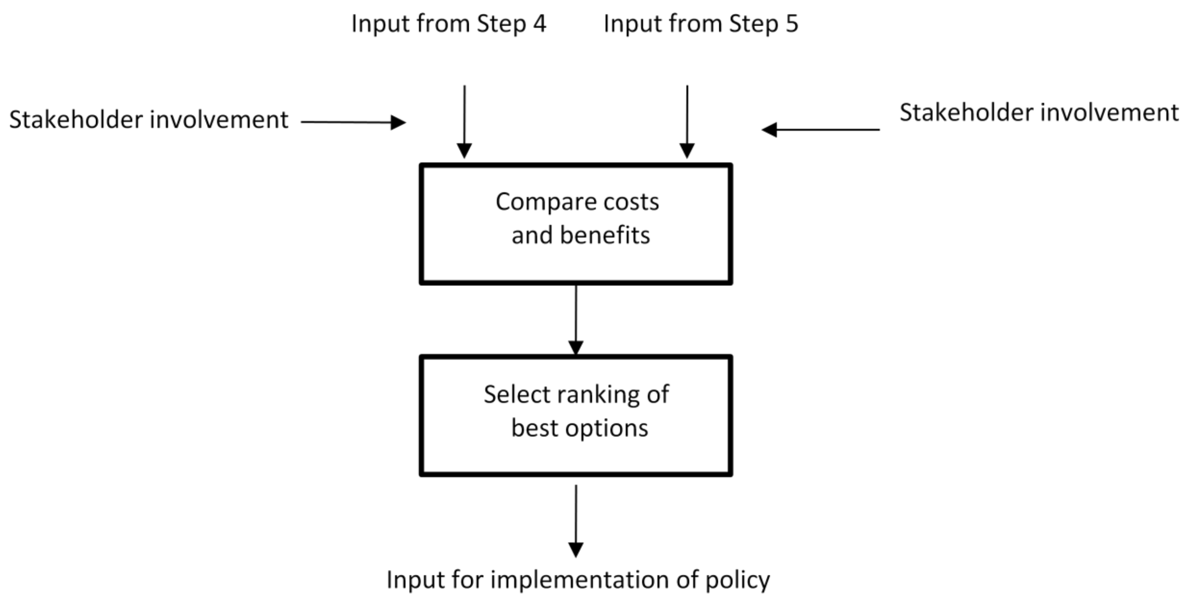

Figure 26 Selection of the best solutions scheme.

Once the alternative options and effects are determined, the best set of measures is selected for input for implementation. Based on the effects on the measure or set of measures and the dialogue of stakeholders, the best solution is selected. The evaluation of the measure (or set of measures) that is preferred should be related to pre- defined criteria, such as cost- effectiveness analysis (only costs and concentration reductions), or costs- benefit analysis (if other effects than costs and concentration reductions).

The different types of impacts should be compared. A sensitivity analysis should be undertaken to test whether different estimates could affect the conclusions, and how significant such difference is. Uncertainties should be identified and described at the various steps of the analysis. In general, the level of detailed analysis should reflect the problem and on how close the balance of costs and benefits are. For instance if the (initial) assessment indicate that benefits are significantly larger than the costs, a conclusion might be drawn on a more qualitative basis.

The quality of the data obtained should be as far as possible be evaluated. Often quantitative data on qualities and uncertainties are not available and a data quality ranging system should be applied, giving a guide to the confidence in the data.

Box 7 – Data quality ranking system

Data quality rating system:

A. An estimate based on a large amount of information fully representative of the situation and for which all background assumptions are known.
B. An estimate based on a significant amount of information representative of most situations and for which most of the background information are known.
C. An estimate based on a limited amount of information representative of some situations and for which background assumptions are limited.
D. An estimate based on an engineering calculation derived from a very limited amount of information representative of only one or two situations and for which few of the background assumptions are known.
E. An estimate based on an engineering judgment derived only from assumptions.

Box 8 – Net present value

The net present value is the sum of the discounted costs compared to the discounted benefits, presented in the following formula;

$$NPV = \frac{R_t}{(1+r)^t}$$

Rt – the net cash flow (i.e. benefits minus costs) at time t.

$$NPV = -I + \frac{B_1 - C_1}{1+r} + \frac{B_2 - C_2}{(1+r)^2} + \frac{B_n - C_n}{(1+r)^n} > 0$$

I represent the investment, B is the benefit value, C is the cost value, while r is the discount factor which depends on the time value of money and time preferences. If the discounted benefits exceed the discounted costs, the alternative scenario can be said to be efficient given that all relevant information is included in the assessment.

5 Results

5.1 Step 0 – Problem definition

The problem definition of mercury as well as a reasoning of the required emission reductions are described and evaluated in the „State of art" chapter. In general, there is clear evidence from the global mercury cycle that there is an urgent need for action to reduce anthropogenic mercury emissions. It will be important to evaluate the effectiveness of measures to reduce anthropogenic emissions and to do this within a sound scientific framework, –something that is also recognized at policy level.

5.2 Step 1 – System definition

To capture all relevant upstream and downstream processes that can have a significant effect on the environmental performance within the jurisdiction of the Environmental Commission, the geographical boundary for emission inventories are set for the EU 27 region. Multi- model source attribution studies seem to support that atmospheric deposition levels in Europe are in a large degree affected by emissions outside of the region. At the same time remains Europe one of major sources of mercury deposited in other regions (including the Arctic). The geographical boundaries for assessing negative externalities of mercury are thus set globally.

As identified from previous works conducted by the candidate, the temporal boundary chosen for this thesis is the period of one year in 2005 and in 2020.

The source categories investigated is identified as the major contributors to mercury emissions in Europe. They are identified from previous works conducted by the candidate and the relevant source categories are defined as follows:

- *Fossil fuel combustion*, such as stationary combustion of coal and other fuels associated with energy and heat production in major power plants or small industrial or residential units and heating appliances.
- *Non- ferrous metals production*, such as mining and industrial processing of ores, in particular in primary production of non- ferrous metals production (especially copper, lead and zinc smelting) but also fuel consumption. It also includes large scale production of gold.
- *Iron and steel production*, such as in primary production of iron and steel and fuel (coke) production and consumption.
- *Cement production*, such as combustion of fuels (mostly coal but also a range of wastes) to heat the cement kilns.
- *Chlor- alkali production* using the mercury- cell process.
- *Product use,* such as batteries, measuring and control devices, lamps, electronically and electronic devices, dental amalgam and others.
- *Incineration of mercury- containing wastes* from various uses of mercury in various consumer products as well as cremation of corpses containing dental amalgam.
- *Other sources*, such as other wastes and agricultural wastes, production of fertilizers etc.

Processes or uses of mercury that have no significant effect on the outcome of the analysis are excluded.

5.2.1 Identification of stakeholders

The main stakeholders identified for the decision support system towards environmental policy on mercury in Europe are understood to be the European Commission (through directives), the international community such as UNEP as well as various international conventions such as the UN Economic Commission for Europe (EC) Long-range Transboundary Transport of Air Pollution (LRTAP), Stockholm convention, Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM), the Paris Commission for the Prevention of Marine Pollution from land-based Sources (PARCOM), Oslo and Paris Convention for the Protection of the Marine Environment of the North- East Atlantic (OSPAR), national governments, and companies and individuals involved in the management throughout their life cycles from all relevant sectors. Individual stakeholders include consumers, disposers, employers, farmers, producers, regulators, researchers, suppliers, transporters and workers. In addition can those indirectly affected by implementation of the policy be regarded stakeholders.

5.3 Step 2 – Inventory of sources

5.3.1 Data collection

Information on primary anthropogenic emitted mercury to the environment in the EU 27 is generally prepared by national experts and reported within the UN ECE LRTAP European Monitoring and Evaluation Programme (EMEP). Furthermore, information on mercury releases has been collected by member states under various international conventions and formed treaties such as the Aarhus Protocol to the LRTAP convention, PARCOM, OSPAR, HELCOM, and the UNEP Mercury Programme.

To determine the European mercury emissions to air from anthropogenic sources in 2005, the following available information were used by the candidate:

- UN ECE EMEP[8]
- National data submitted to the UNEP chemicals from Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Italy, Latvia, Moldova, Netherlands, Romania, Slovakia, Sweden, and the United Kingdom.
- EU25 European Pollutant Emission Register (EPER) / European Register of Pollutant Release and Transfer (E-PRTR)[9].
- EU Project ESPREME[10].

National responses to the UNEP Chemicals were collected through the UNEP, (2008a) work on providing a global mercury emission inventory, lead by the candidate and other researchers at NILU. These results are presented in Pacyna et al., 2010a. For verification of emission data reported from national emission experts, estimates were in these works obtained from statistical data on consumption on raw materials or production of industrial goods and data on the likely emission factors (e.g. the EMEP/CORINAIR, (2007) Atmospheric Emission Inventory Guidebook). An overview on the results from the collected data on emissions from the EU- 27 is illustrated in Figure 27 below. Country-specific emissions can be observed in the Appendix. Figure 28 illustrates the atmospheric emissions of mercury from European point sources.

[8] http://www.emep.int (Accessed June 2010)
[9] http://eper.eea.europa.eu/eper (Accessed June 2010)
[10] http://espreme.ier.uni-stuttgart.de (Accessed June 2010)

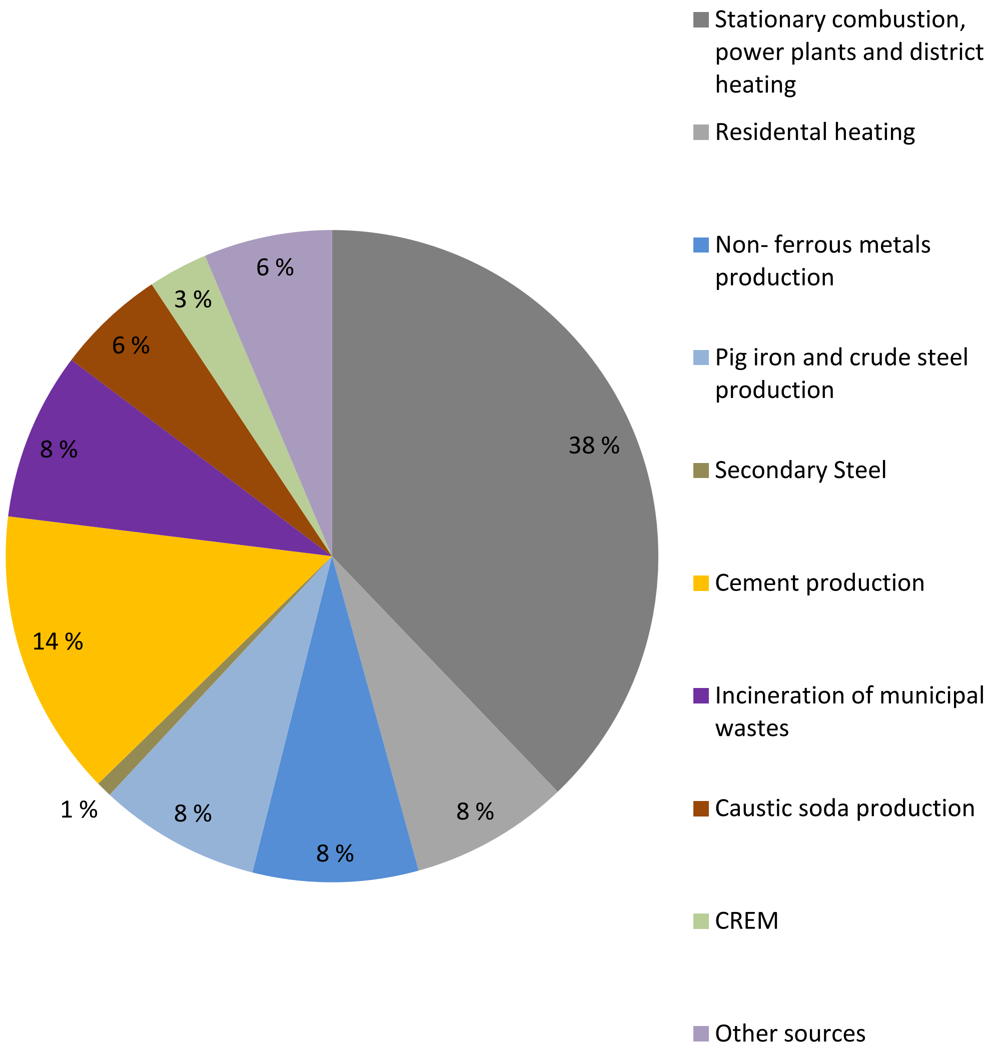

Figure 27 **Collected and estimated data on atmospheric emissions from anthropogenic sources in the EU27.**

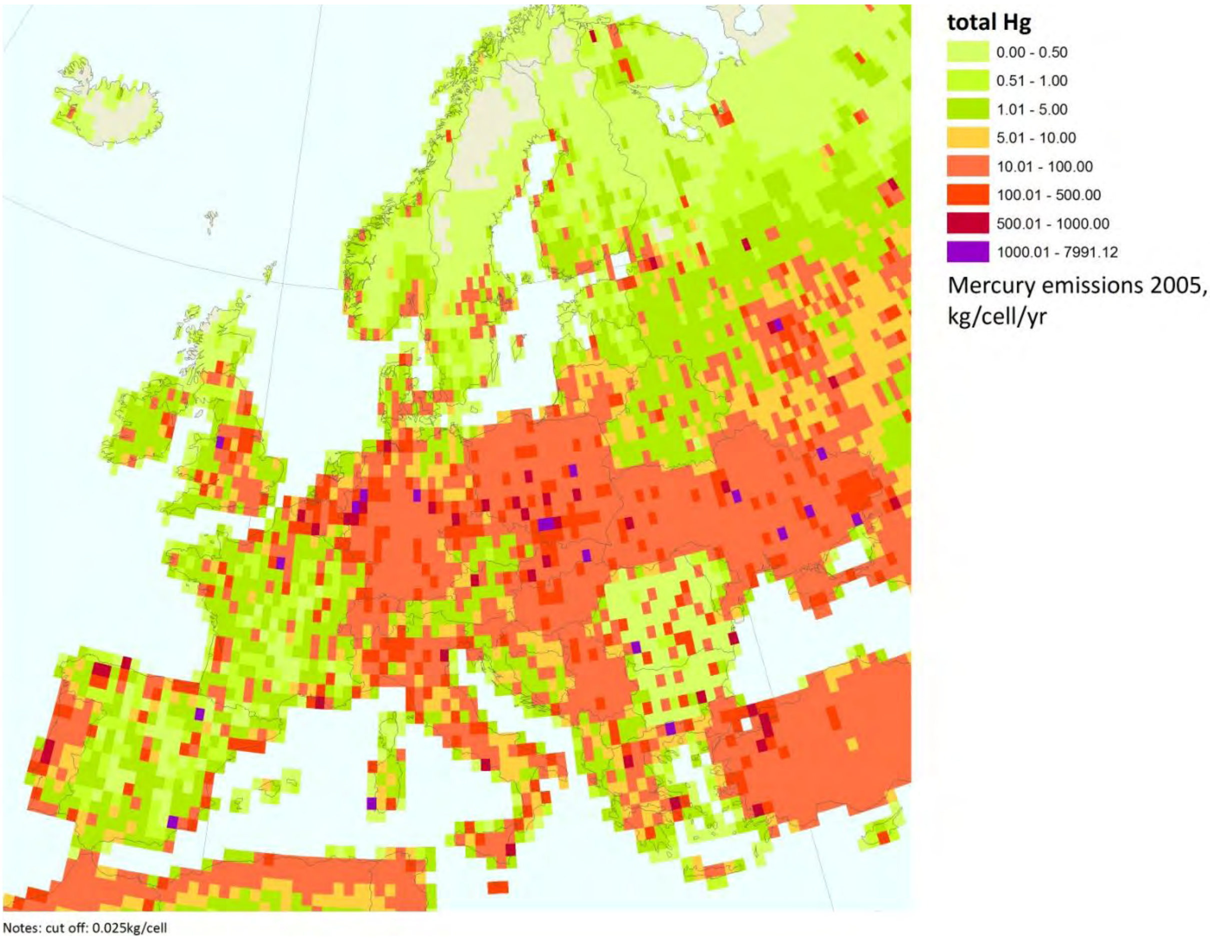

Figure 28 Atmospheric emissions of mercury from European point sources (Figure provided by Frits Steenhuisen).

Anthropogenic (direct) mercury emissions to the atmosphere from the EU 27 countries in 2005 were about 106 tonnes. Most emissions (about 40%) occur from fossil fuel combustion, mainly coal in power plants for electricity and heat production. Residential heating adds about 8% to this estimate. Cement production emits 14 % while other industrial processes, such as non- ferrous metals production, pig iron and steel production as well as incineration of municipal wastes is responsible for about 8 %, while less is reported for caustic soda production, cremation and other sources.

Less recent data has been reported for mercury discharges to water and soils. For industrial sources being under the EU Integrated Pollution Prevention and Control (IPPC) Directive, mercury emissions released directly into air or water, or indirectly to water are reported to the E-PRTR. This data, however, are only values above a given threshold (of 10 kg year-1 for releases to air, while 1 kg year-1 for releases to water and land) and thus represents only a fraction of the true amount. The candidate therefore had to use expert judgment on some of these flows.

5.3.2 Determination of mass flows and balancing of goods

Mercury enters stationary fossil fuel combustion (mainly coal in utility, industrial, and residential boilers) from existing naturally as a trace contaminant in coal, oils and natural gas. Most large power and heat plants (>300MW capacity) in the EU 27 are equipped with Air Pollution Control Devices (APCDs) such as Electrostatic Precipitators (ESP) or Fabric Filters (FFs) for particulate control, but many installations also reduce SO_2 emissions through Flue Gas Desulphurization (FGD) systems based on wet or semi- dry scrubbers. In modern power plants, selective catalytic reduction (SCR) is used for controlling NOx, enhancing mercury capture of a downstream FGD (Weem, 2010). The European IPPC Best Available Techniques reference document (BREF) for Large Combustion Plants (under the IPPC directive; EC, (2006)) concludes that the use of Best Available Techniques (BAT) for the EU member states would be to apply the most effective techniques to reduce SO_2, PM and NO_X emissions, but still many large combustion plants do not apply the full range of abatement techniques. To give a complete picture of how much mercury being removed from the flue gases, detailed information on the equipment configuration and implementation degrees are in addition to information on coal type and chlorine (and bromine-) contents in the coal required (Pavlish et al., 2003). In general, sub- bituminous and lignite coals demonstrate lower mercury capture than similarly equipped bituminous- fired units (UNEP, 2010).

Direct industrial discharges of mercury to the aquatic environment is for large combustion plants usually related to effluents which origin from water use in the cooling circuit systems, in the steam generating process, and in flue- gas cleaning systems. According to Nriagu and Pacyna (1988), coal burning power plants discharges mercury by an emission factor of 0-0.6 ng l-1, largely depending on the type of air pollutant technology in use and the type of effluent treatment in place (Nriagu and Pacyna, 1988).

Mining and industrial processing of ores, such as primary production of non-ferrous metals (copper, lead and zinc smelting) and iron and steel (mainly coke production) releases most of the mercury as a trace metal being present in the metal ores. Less significant amounts are released from the sector- use of fossil fuels (UNEP, 2010). The content of mercury in ores varies substantially from one ore field to another (e.g. Pacyna, 1986) as does the mercury content in scrap used for secondary non- ferrous production. The fate of the mercury is to a large extent determined by the industrial technology employed. If high temperature processes (i.e. roasting and sintering) are used in the initial treatment of the ore, most of the mercury in the concentrate is expected to evaporate from the oxidation and follow the gas stream which in various degree can be captured by APCDs (e.g. by FFs, ESPs, or scrubbers – leading to either dry solid wastes or sludge containing mercury), whereas if electrolytic (hydrometallurgical) processes are used for non- ferrous metals production, the mercury will remain in the liquid phase and thus imposes a higher risk for water contamination (UNEP Chemicals Branch, 2005). No data however, has been identified on mercury emissions from the electrolytic step.

According to the BREF, gas cleaning of smelters and roasting stages are the most important sources of waste water (EC, 2001b).

Mercury specific removal techniques may be installed in sulphur acid plants. According to Hylander and Herbert (2008), the assumed removal of mercury is 10% if no or limited sulphur removal devices are installed. The mercury removal step can also lead to discharges through waste water. The liquid reagent for mercury removal typically contains 0.1-0.9 mg mercury /l before the treatment.

Production of metallurgical coke is the major source of atmospheric mercury from iron and steel industry (Pacyna et al., 2010a). The amounts of trace elements that is being released is in a large degree depending on the steel making technology being used, whereas the electric arc (EA) process has the largest atmospheric emitting potential (compared to the basic oxygen (BO) and open hearth (OH) processes). ESPs or FFs and less frequently wet scrubbers, are used in the coke production plants to control emissions, particularly those generated during quenching. Although no data are available for the performance of the ESPs or FFs in coke production plants, it is expected that mercury removal is limited (UNEP, 2010).

Mercury enters the cement kiln either as naturally present in minerals (e.g. limestone, marl and chalk) or from being present in fuels (mainly pulverized coal, petroleum coke, heavy fuel oil and gas, but also less expensive fuels like shredded municipal garbage, chipped rubber, and waste solvents) whereas it leaves the kiln with the dust and exhaust gas (Pacyna et al., 2009). Mercury concentrations in minerals are assumed to be between 0.01 and 0.15 mg mercury per Kg (EC, 2010). The relative contributions of emitted mercury from the use of fuels and minerals varies between kilns, but 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 % of the kilns, non- limestone mercury accounted for greater than 50 % of the kiln`s mercury emissions (i.e. origins from other minerals or from fuels). According to the UNEP Paragraph 29 study, ESPs or FFs are most commonly used for mercury control, but also use of SNCR and wet and dry scrubbers for SO_2 removal has been reported (UNEP, 2010). Cement kiln dust removed from the stack gas in cement production is to a large extent being re-circulated into the process. Mercury-containing fly-ash is sometimes added to cement following the production process.

Mercury is present in various wastes in highly variable concentrations in different countries, mainly depending on the existence of systems for collection of mercury or if the products are disposed to the regular waste stream (UNEP, 2010). The Larssen et al., (2008) report states that most of end-of-life treatment of consumed mercury is distributed in disposal pathways other than municipal waste disposal/incineration, such as in hazardous waste deposits and hospital waste incineration. In the EU countries, the household waste is not generally mixed with medical waste. Removal efficiencies for controls in waste incineration plants are in the UNEP Paragraph 29 study presented as small for the use of ESPs, while using wet scrubbers or spray absorbers using limestone for acid gas removal efficiencies ranged from 55-65 and 44-52 % respectively. More than 90 % mercury removal can be achieved by the addition of special absorbents, such as activated carbon, -something that according to the UNEP Paragraph 29 study are quite common for those countries were large scale waste incinerators are used (UNEP, 2010).

Intentionally used mercury may circulate in society (producer stocks included) for many years before it enters the waste systems. A market supply of mercury in Europe may originate from imports, by-product recovery, closure of chlorine production capacity, and recycling from the waste stream (Pirrone and Mahaffey, 2005), as well as from commercially held stocks of mercury. The major uses of mercury in Europe (EU-25) in 2005 includes chlor- alkali production using the mercury- cell process, dental amalgams, chemicals, batteries, measuring equipment, light sources, and switches, relays etc. (AMAP, 2010). In total, the EU-27 intentional use of mercury mass balance for 2005 shows a consumption of 400-460 tonnes whereas 170 (including 35 tonnes reused) tonnes are liquid mercury for use in chlor- alkali production Larssen et al., (2008). In the estimate, 77 tonnes mercury in products was imported to Europe while 151 tonnes was exported in products (Larssen et al., 2008).

The mercury- cell chlor alkali plants that are still in operation (2005) in Europe contain a stock of 11 000 tonnes of mercury. In 2009-2010, this stock has been reduced to 8 000 tonnes of mercury. It has been reported that about 40 - 50 tonnes of the mercury consumed in the chlor alkali industry is being unaccounted for in 2005, -losses that most probably represent unrecorded fugitive emissions to water, atmosphere and waste disposal (Larssen et al., 2008).

It is in the analysis assumed that none of the extracted ores and fuels containing mercury as a trace pollutant are accumulated in stocks over time, meaning that these are instantly consumed in industrial production and thus equals the emitted mercury within the same year as geologically extracted. Historical contamination (e.g. from former industrial activities, generating background concentrations) or diffuse pollution sources that are circulating in the society are not included in the estimates. Also, concentrations of mercury unintentionally embodied in the industrial product flows in the society (e.g. in cement or in ferrous or non- ferrous metals) are not considered in the estimate as the literature supports that mercury is being retained and do not pose any significant risk of leaching to the environment (see e.g. Senior et al., (2009) on the fate of mercury collected from air pollution control devices for the case of mercury in fly ash). It should be kept in mind that scrap metals being recycled may still be a source of mercury emissions but to a much lesser extent than from primary metals production.

Emissions generated from the secondary anthropogenic source- category in products are mainly estimated by linking information on consumption of various mercury- containing products (S) to the methodology described in (Kindbom and Munthe, (2007)), i.e. using distribution factors to allocate the mercury- containing products into different waste treatment categories and subsequent attribute to them atmospheric emission factors on breakage, metal scrap smelting, waste incineration and land-filling. (See Kindbom and Munthe, 2007 for complementary information). Additional information on stocks and flows of mercury uses and mercury- containing products are in this thesis collected from various literature sources, such as the Directorate-General (DG) Environment reports; Maxson, (2006) and Larssen et al., (2008). A Stock-Flow model approach is applied for developing future projections on emissions, discharges and releases from mercury used intentionally in products, whilst at the same time accounting for the mercury accumulated in society (i.e. in the use phase).

Mercury cycling between different environmental compartments depends on the dynamic of chemical and physical processes (oxidation, dry deposition, wet scavenging). Exchange of the mercury between different environmental reservoirs (atmosphere, water, and land) is in this thesis based on a greatly simplified mass balance technique based on fixed exchange rates between the environmental compartments.

5.3.2.1 Substance flow diagram

A European Union (EU 27) wide Substance Flow Analysis (SFA) on major sources, flows, and environmental endpoints of mercury in Europe has been presented by the candidate in Sundseth et al., 2012. In case of inadequate atmospheric emission data reported, alternative estimates were obtained by the candidate from statistical data on consumption on minerals or production of industrial goods and data on emission factors (see Pacyna et al., 2010a for more information on the methodology). A Stock-Flow model approach (see e.g. Muller , 2006), were applied for developing future projections on emissions, discharges and releases from mercury used intentionally in products, whilst at the same time accounting for the mercury accumulated in the EU 27 society. Figure 29 illustrates a simple SFA map on mercury in the EU 27.

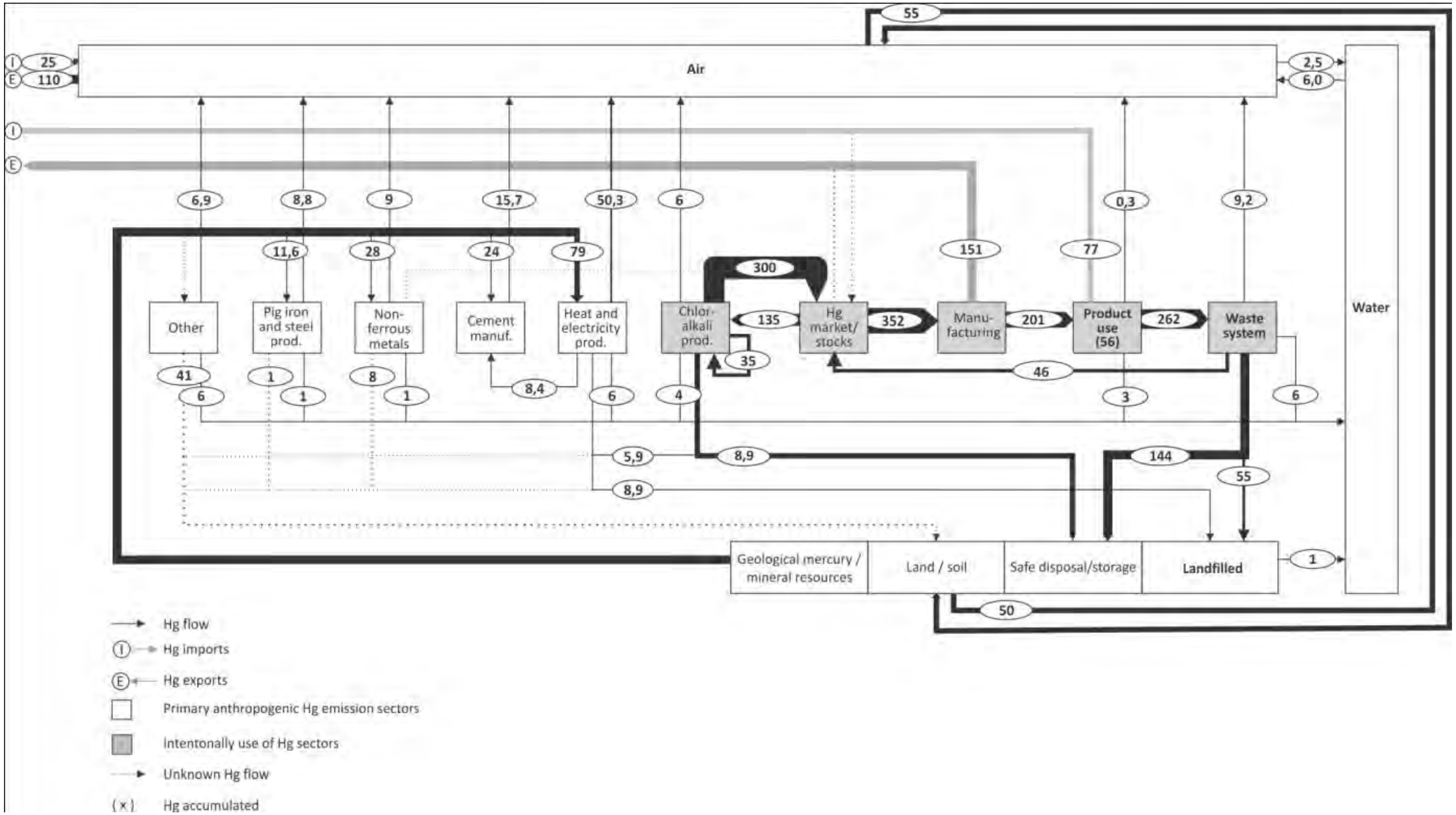

Figure 29 A simple SFA diagram on current (2005) mercury flows and emissions in the EU 27, as presented in Sundseth et al., 2011.

Based on the findings, the direct anthropogenic emissions to the atmosphere, such as high temperature processes like stationary combustion of coal, associated with energy or heat production in major power plants, small industrial or residential heating units as well as in various industrial processes, are the largest source categories. Only a small fraction of the mercury emitted to air is directly released from the use phase of mercury- containing products. A significant amount of atmospheric mercury is naturally emitted or re-emitted from soil- and vegetation-, as well as water and sea surfaces (50 tonnes and 6 tonnes respectively).

The majority of direct discharged mercury to water originates from power plants utilizing water for cooling circuit systems, steam generation process and flue gas cleaning systems as well as runoff from (urban/municipal) waste treatment systems. Fewer quantities of direct discharge to water can be traced to wastewater effluents from primary non-ferrous metal smelters (direct and indirect cooling water, electrolysis, hydrometallurgy and waste water from flue gas cleaning systems) and iron and steel plants (waste water from flue- gas cleaning systems). Other direct releases arise from chlor- alkali production and amalgam used for dental purposes. The „other" sector- source, such as manufacturing processes of metals, chemicals and petroleum products, and agriculture related sources are together accounting for more than 20 %. A significant contribution to the balance was found to indirectly origin through atmospheric deposition and to a less degree; runoff from wastes deposited on landfills. Even though not quantified, ocean currents that represent a long- distance transport pathway may also be important for the EU oceanic mercury mass balance.

Mercury flows to the soil is in a large degree connected to waste treatment and disposal of bottom- ash and fly- ash collected from PM control equipment (such as ESPs and FFs) at fossil fuel combustion and waste incineration facilities. Combustion residues can be disposed to landfill or it can be utilized in construction industry (concrete, cement and road construction), or for restoration of open cast mines, quarries and pits. However, there is little information on the ultimate fate of mercury captured though various types of control technology and about how the mercury- containing wastes are subsequently disposed of. Reducing mercury emissions to air by capturing ash and particles from power plant stack gases requires for many cases the disposal of potentially hazardous waste.

5.4 Step 3 – Definition of a baseline scenario

5.4.1 The key drivers

Future mercury emissions in the EU are dependent upon a great number of variables, including introduction of legislations and directives, technology change, and demographic changes, development of the economy, and consumption increase or decreases. Even though actual compliance is difficult to estimate, large efforts are in many EU- countries already being made to reduce mercury emissions by reducing its use in products or by implementing measures that prevent mercury from being emitted from various industrial production processes. It is also expected that a number of additional technological and non- technological measures as well as policy options will be employed as a result of national and international initiatives to reduce greenhouse gases e.g. through improvement of energy efficiency in power stations, replacement of fossil fuels by renewable sources, and improvement of combustion processes, -which eventually will influence mercury emissions indirectly. In assessing future emissions based on the baseline scenario, the following main drivers have been identified:

- International and regional legislations, directives and regulations on mercury. (An overview of the relevant ones can be found in the Appendix), leading to
    - Technology change, such as those required by the European IPPC Best Available Techniques reference documents (BREFs) for the use of Best Available Techniques (BAT) for the EU member states.
    - Consumption and substitution effects.
- Changes in the demand for fuel consumption (affected by prices, changes in population and the development of the economy).

The European emission reduction scenario defined as the Baseline scenario was projected for 2020 by the candidate. More details on future emission scenarios can be found in Sundseth et al., (2010). The main baseline scenario assumptions are made on future expectations on economic and social development as well as expectations on fulfilled implementation of the planned policies for the EU 27 region. This includes certain measures adopted under the LRTAP conventions, the EU directives, and also agreements to meet the IPCC Kyoto targets on reduction of greenhouse gases that will indirectly cause reduction of mercury emissions.

5.4.2 When does the change occur?

The European Commission has published an energy baseline scenario up to 2030, derived from the energy system model PRIMES (DG TREN, 2003; DG TREN, 2008) in which the main assumptions comprise projections for economic growth, demographic developments and fuel consumption (prices), and EU policies. Changes of control technologies for mercury emission to the atmosphere were presented in DROPS BAU+Climate (Business as Usual with Climate Policies) scenario (Panasiuk et al., 2006), in which atmospheric mercury emissions for this scenario were estimated by Strzelecka-Jastrzab et al. (2007).

Population growth in EU27 is projected to be low with a population peak in 2020 at 496.4 million and a total of 471.8 million in 2050. Average household size is projected to decline from 2.4 persons in 2005 to 2.1 persons in 2030 (DG TREN 2008).

Economic growth is projected at 2.2% on average up to 2030. This scenario is considered to be optimistic, assuming that EU 27 benefits from the Lisbon economic reform process, from the completion of the Internal Market and from a continued increase in world trade reflecting globalization and the removal of trade barriers. The GDP projections for EU 27 are based on forecasts by the DG Economic and Financial Affairs giving a projected GDP per capita growth rate of 1.7 for EU-25 in 2004-2050.

5.4.3 The effects from the changes in key drivers

For electricity generation until 2020 it is projected that there will be a production decrease in conventional heat and electricity plants close to the (DG TREN, 2003) projections for coal-fired thermal open cycle plants. In the same period, an increase of gas combustion in combined cycle gas turbines (GTCC) and in the use of clean coal technologies (integrated gasification combined cycle – IGCC) is expected. Due to the BAT reference document (EC, 2006b), large coal-fired combustion plants will be equipped with FFs or electrostatic precipitators ESPs operated in combination with FGD techniques. In conventional pulverized boilers additional techniques designed for metal removal (activated carbon, sulphur-impregnated adsorbents and selenium impregnated filters) will be implemented.

Best available techniques for reduction of emission to atmosphere will until year 2020 also be implemented in other industrial sectors, such as; FFs and dry ESPs in iron and steel (EC, 2001a) and cement industry (EC, 2001c, and EC, 2010), mercury removal in installations of sulphuric acid production and FFs in non-ferrous metal industries (EC, 2001b) and conversion of mercury cell plants to membrane cell technology in chlor-alkali industry (EC, 2001d). Additionally, catalytic oxidation will be implemented in ferrous ores sintering and FGD techniques in cement industry.

Implementation of the EU directives concerning mercury-containing products will in combination with social campaigns decrease the manufacturing and consumption of mercury- containing products until 2020. According to directive 2007/51/EC, mercury in thermometers or in other measuring devices intended for sale to the general public shall not be introduced to the market. In effect a 70% decrease of the EU consumption of measuring and control devices is expected. A wide introduction of mercury-free alternatives, such as button cells (silver-oxide, zinc-air and alkaline) is projected to decrease mercury consumption in batteries by 70%. According to directive 2002/95/EC and decision

2005/618/EC since 2006, mercury shall only be used in electrical and electronic equipment, in fluorescent lamps with reduced mercury limits per lamps and in other equipment with maximum concentration value of 0.1 % by weight in homogeneous materials. Simultaneously Regulation 244/2009 is expected to cause an increased consumption of compact fluorescent lamps. This means that a stabilization of mercury consumption for lighting while a 50% decrease for remaining electrical and electronic equipment is expected by 2020.

The implementation of a new legislation is also expected to change the mercury flows in the waste systems. An achievement of 45% collection rate of batteries and accumulators is expected for the EU member states due to directive 2006/66/EC, while the WEEE directive 2002/96 sets a minimum collection target of 4 kg on average per inhabitant per year of waste electrical and electronic equipment from private households. For example to achieve this target, a 40% collection rate for lamps and a 24% rate for other equipment have been set for the Polish national legislation. In new EU member states, the share of incineration of municipal wastes is expected to increase. For waste incineration the use of suitable metal removal techniques is demanded by BREF for this sector (EC, 2006c).

Decreased mercury consumption is expected in dental practice as a result of partial substitution of dental amalgam by polymer composite fillings. Implementation of dental amalgam separators will help to decrease mercury discharges to water and also to decrease the volume of medical infectious wastes and the resulting mercury emission from waste incineration. Dental amalgam captured and separated will be safely stored.

Mercury discharges to water were for the baseline scenario estimated in HEIMTSA, (2009). Good practice in large combustion plants is recycling of the cooling waters and reuse of the effluents from FGD units (EC, 2006b). Implementation of BAT is also expected for the chemistry industry. In chlor-alkali industry (EC, 2001d) BAT is considered as membrane or non-asbestos diaphragm technology. During the remaining life of mercury cell plants, minimizing the amount of waste waters and treatment of all mercury-containing waste water streams will be taken. For production of NPK fertilizers minimization of waste water volumes by recycling, washing and rinsing waters and scrubbing liquors is projected. Recycling of scrubbing liquids is expected for production of superphosphates (EC, 2007).

In municipal waste waters monitoring of sewerage systems is projected for reducing of illegal mercury discharges from small-scale industry and services. The upgrade of wastewater treatment plants by fluidized bed sludge incineration facilities should also reduce heavy metals emissions to the atmosphere from waste waters management (Balogh and Nollet, 2008).

5.4.3.1 Environmental fate

Mercury circulating between the environmental reservoirs air, water (freshwater and ocean) and (surface) soil is ultimately being stored by deep burial in soils and ocean or lake sediments. How mercury moves between these compartments and reservoirs depends on the pathways and processes that connect them (AMAP, 2011). In general, the atmosphere responds much faster to changes in emissions compared to water and soil and is thus the dominant mercury transfer pathway.

Once deposited, inorganic mercury is transformed by micro bacterial processes to bio available forms, such as methylmercury which can be further taken up by living organisms in ecological food- webs and chains. The rate of methylmercury production and its transfer within food- webs is variable. Little is known about mercury dynamics and pathways in the atmosphere and ocean.

5.4.3.2 Emission/concentration trends

Global emission trends to the atmosphere has been presented for the nominal years 1990, 1995, 2000, and 2005 in Pacyna and Pacyna, (2002); Pacyna et al., (2006); and Pacyna et al., (2010a), and later updated, consistently structured and re-evaluated by the candidate in the Arctic Monitoring Assessment Programme (AMAP, 2010a) report. According to the report, European mercury emissions to the atmosphere from both industrial sources and from intentional uses have shown a decreasing trend over the period 1990-2005. The trend has furthermore been confirmed by mercury measurement data (e.g. Pacyna, Pacyna and Aas 2009). The emission decrease from European industrial sources has mainly been linked to the implementation of FGD equipment in the energy producing sector in addition to emission controls in other industrial sectors, combined with a downward economic trend in Eastern and in Central Europe (Pacyna, Pacyna and Aas 2009). On the contrary, multi- model source attribution studies seems to support that concentration levels in Europe are in a large degree affected by emission- increases outside Europe, -especially from increases in the South- East Asia region (AMAP, 2010b).

The intentionally use of mercury continues to decline in the EU 27 as mercury- free alternatives are available or being reinforced by legislation for nearly all such applications. Many countries have implemented policies to mitigate the problems related to diffuse mercury releases such as those associated with disposal of mercury-containing products. With emphasis on mercury being discharged to the waste water systems, some countries have implemented measures to greatly reduce the use of dental amalgams containing mercury. However, the rate of decline varies widely; mercury use in dental applications is still significant in many countries, while in some countries, e.g. Sweden and Norway (not an EU- member state) it has almost ceased. Overall, the total consumption of mercury- in 2005 has in the EU-25 declined by 79 % since 1990 (AMAP, 2010a). The largest decline since 1990 has been observed in VCM and acetaldehyde processes (100 %), mercury- containing electrical and electronic switches and relays (95 %) and batteries (93 %), followed by measuring and control devices

(86 %), and in other compounds (such as; catalysts, medicine, pesticides and chemical intermediates, 60 %), and in lightning/lamps (AMAP, 2010a). Mercury-containing lamps (fluorescent tubes, compact fluorescent, high-intensity discharge lighting) remain the standard for energy-efficient lamps, where ongoing industry efforts to reduce the amount of mercury in each lamp are countered, to some extent, by the ever-increasing number of energy-efficient lamps purchased and installed.

As there are variations in natural mercury emissions worldwide, it is difficult to measure the changes in environmental concentrations resulting from changes in anthropogenic European emissions alone. Studies from mercury measurements in ice from the Greenland ice sheet and Canadian lake sediments have indicated that mercury deposition (from global sources) in the Arctic peaked in the 1970 and then declined sharply from the introduction of clean air policies. The measurement levels have been fairly stabile since the mid 1990s, which somewhat reflects the emission trends. Biotic trend studies (mainly in the Arctic) have shown that concentrations are varied depending on the type of animal and geographical locations, but suggest increasing trends for some marine species and predatory freshwater fish species.

5.4.3.3 SFA diagram on future (Baseline 2020) emission sources and loads.

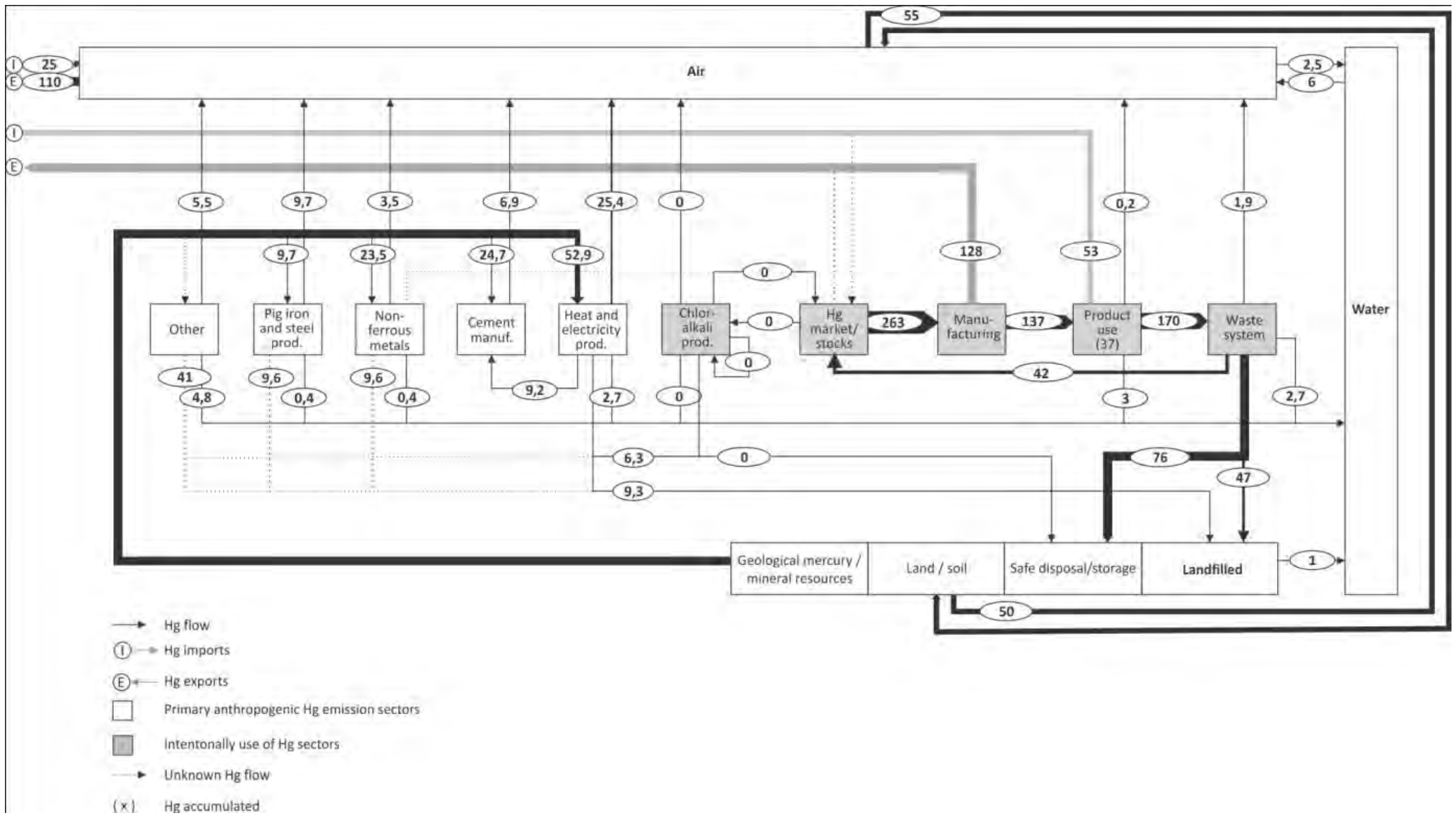

Figure 30 **A simple SFA diagram on future (Baseline 2020) mercury flows and emissions in the EU 27, as presented in Sundseth et al., 2012.**

Clear decreases in mercury emissions between 2005 and 2020 are expected for all relevant source categories under the Baseline scenario. Emissions of mercury as a trace contaminant in fuels and minerals are becoming increasingly important to the environmental concentrations compared to the emissions from mercury used intentionally. The 2005 estimate of 27 tonnes direct emissions of mercury to water is projected to decrease about 50 % for the baseline scenario. The largest decrease is due to the reduction of intentionally used mercury (in chlor- alkali production in particular). Mercury in products accumulated from previous year"s consumption is estimated to decrease by 34 %. Mercury separated from the waste systems is to a large degree safely stored.

5.5 Step 4 – Inventory of possible measures

Because of the large number of possible measures to reduce mercury emissions in the various sectors in different countries, it is too ambitious in a PhD thesis to present a comprehensive inventory of measures with associated investment and Operational and Maintenance (O&M) costs. A simple evaluation of an alternative technical option in coal power plants and industrial boilers in the EU is therefore applied as an example of the step. Mercury emissions from this sector constitute the largest amount of atmospheric mercury emissions in the EU, also estimated for the Baseline scenario.

Coal combustion utilities apply a variety of combinations of APCDs that simultaneously control mercury or that specifically control mercury. The *Coal Power*[11] database which contains records over European coal fired power facilities is used by the candidate to extract information of the applied pollution controls and their implementation degrees in 2010. Expected implementation degrees for the use of the most typical techniques for the year 2020 have been obtained from personal communication with industry representatives being familiar with the technological development in the sector. Mercury removal efficiencies have been assumed from ranges in limited tests conducted at facilities in the USA as well as experiences from previous works by the candidate. The alternative situation assumes 100 % implementation of sorbent injection technologies by 2020. The information is presented in Table 4 below.

Table 4 Technology implementation degrees and mercury removal efficiencies from measures in the coal combustion sector for the EU 27 in 2010 and in 2020.

Measure	Implementa - tion degree (%)	Removal efficiency (%)	Implementa - tion degree (%)	Removal efficiency (%)	Implementa - tion degree (%)	Removal efficiency (%)
	Baseline 2010		Baseline 2020		Alternative 2020	
ESP/FF	100	15	100	15	100	15
ESP/FF +wet scrubber	90	50	100	50	100	50
ESP/FF +wet scrubber + sorbent injection	10	99	50	99	100	99

The overall removal of mercury from the flue- gas in electric utilities in the EU 27 in 2010 is estimated to about 50 %. The most commonly used abatement technique is the use of de-dusting control (90% ESPs), as well as combining de-dusting control combined with desulphurization (90% of the facilities with installed de-dusting control), abating about 15% and 50% of the mercury

[11] Hosted by IEA Clean Coal Centre http://www.iea-coal.org.uk/site/2010/databases?LanguageId=0. Visited 08.03.2012. It holds information on more than 2,300 coal-fired power plants, 7,000 individual units and 1,300 addresses throughout the world.

respectively. About 10% of the electric utilities combining de-dusting and desulphurization also optimizes mercury control by adding a sorbent such as activated carbon, leading to a mercury removal up to 99 %.

In 2020 the implementation degrees of de-dusting control is maintained while the combination de-dusting and desulphurization is expected to be applied in all facilities. Dedicated mercury abatement through sorbent injection is expected to constitute 50% of these, leading to about 75 % overall removal from the flue- gas in the electric utilities. Since all the facilities are assumed to have implemented 100 % de- dusting in combination with desulphurization under the Baseline scenario in 2020, the only reasonable option for enhanced mercury abatement in 2020 is the use of sorbent injection as a dedicated mercury abatement technique. The alternative 2020 scenario assumes further that all the facilities implements mercury specific abatement through sorbent injection, - abating almost all the mercury (>99 %) in the flue gas.

5.5.1 Mercury emission control costs

Cost data on the mercury control options exemplified for the coal combustion sector has been obtained by the candidate from the Integrated Environmental Control Model (IECM)[12] developed by the National Energy Technology Laboratory (NETL). These costs have originally been obtained from experiences made by the Northeast States for coordinated air use management (NESCAUM) group from American projects founded by the U.S. Department of Energy among others. For use in policy making, further investigation of these costs is envisaged. The annual investment and operational and management costs from introducing the control options are presented in Table 5 below.

Table 5 Annual investment and operational and management costs from the use of control options

Emission control technology	(USD 2010/MWhe)*		
	Investment cost	O&M costs	Total cost
CS-ESP	0.6	0.4	1.0
FF	1.3	0.7	2.0
CS-ESP & wFGD	3.3	3.2	6.5
CS-ESP & wFGD & ACI**	4.7	8.1	12.7

*Reference: IECM. Cost data estimated for a 600 MW (net electrical output) power plant.

**Carbon injection rate of 20 lb C/Macfm

Investment cost reflects in this case the cost of purchasing the equipment and its necessary infrastructure, instruments and controls. In addition they include freight and installation, taxes, as well as engineering fees.

O&M costs reflect labor cost, power cost, maintenance cost, periodic replacement of items, control cost, as well as variable cost from the adsorbing material input. They can be partly offset by the sale of particular by-products of pollution abatement, such as gypsum from wet limestone FGD. Some O&M costs, such as costs of labor and power, are typically country- specific and can to some extent, differ from country to country. Costs are in this thesis primarily based on costs reported from the United States but more accurate country- specific costs may be calculated by adjusting for country- specific GDP/capita Purchase Power Parity. For dedicated mercury removal technologies, such as sorbent injection, these costs are only a small fraction of the total O&M costs and such an adjustment is considered not being necessary. The investment- and O&M cost components for the ACI technology costs estimate above are presented in Table 6.

[12] Database and documentation available at http://www.cmu.edu/epp/iecm/iecm_doc.html (Accessed in May 2011).

Table 6 Costs (in million 2010 USD / year) for an ACI system

Cost components, investments	**Costs (Million 2010 USD/ year)**	**Cost components, O&M**	**Costs (Million 2010 USD/ year)**
Sorbent Injection	3.6	Activated Carbon	14.6
Sorbent Disposal	0.3	Additional Waste Disposal	0.1
General Facilities Capital	0.2	Electricity	0.07
Eng. & Home Office Fees	0.4	Operating Labor	0.06
Project Contingency Cost	0.6	Maintenance Labor	0.0003
Process Contingency Cost	0.2	Admin. & Support Labor	0.02
Preproduction (Startup) Cost	1.3	-	-
Inventory (Working) Capital	0.03	-	-
Total Investment costs	**6.6**	**Total O&M Costs**	**14.8**

5.6 Step 5 – Assessment of the effects of measures

5.6.1 Transport and potential risk

Atmospheric transport represents the dominant pathway for mercury dispersion in the environment. Mercury is also transported by ocean currents, albeit slower than in the atmosphere. European mercury emissions to the atmosphere from both industrial sources and from intentional uses have as mentioned shown a decreasing trend over the period 1990-2005 (AMAP, 2010), but on the contrary, multi- model source attribution studies seems to support that atmospheric deposition levels in Europe are in a large degree affected by emission- increases outside Europe, -especially from increases in the South- East Asia region (AMAP, 2011; HTAP, 2010). According to the multi-model simulations, about 15% to 25% of the atmospheric mercury deposited to Europe originates from (primary) anthropogenic emission sources elsewhere in the world (HTAP, 2010). At the same time, it is important to have in mind that Europe remains one of the major sources of mercury deposited in other countries or regions, including the Arctic. Receptor regions of mercury deposition from primary anthropogenic and natural/secondary emission sources are illustrated in Table 7 (based on the GLEMOS model simulations).

Table 7 Receptor regions of mercury deposition from anthropogenic and natural emission sources (based on model simulations with the GLEMOS model in HTAP, (2010).

	Deposition of mercury over the globe from European emission sources (% of total European emission)		Deposition of mercury to Europe from domestic and external emissions sources (% of total deposition to Europe)	
Regions	Primary anthropogenic sources	Natural/secondary	Primary anthropogenic sources	Natural/secondary
Europe	14.8	1.6	34.3	3.7
Asia*	5.0	4.1	10.8	7.7
Africa	3.6	3.2	1.0	5.7
South America	1.9	2.4	1.0	2.0
North America	1.5	1.7	1.7	2.7
Australia	1.6	2.0	1.0	2.3
Other*	16.7	39.7	0.3	25.7
Total	45.2	54.8	50.1	49.9

*Includes Central-, East-, and South Asia.

**Includes North Atlantic, the Pacific and the Arctic region.

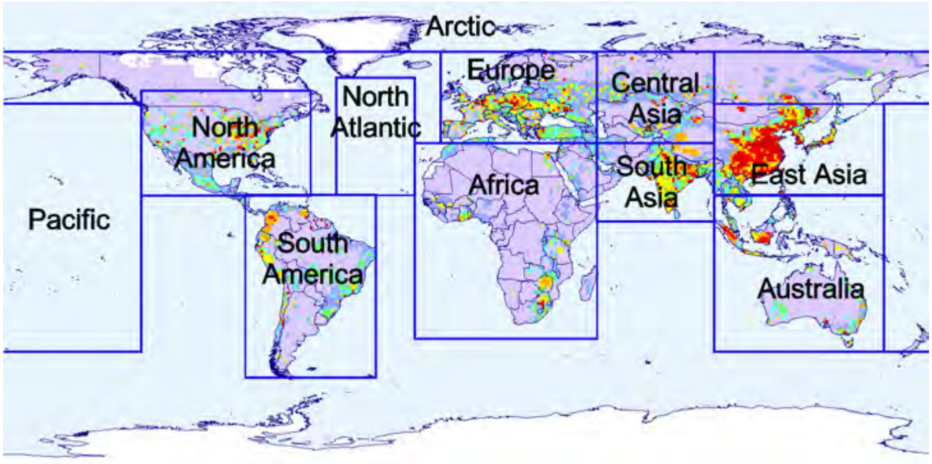

Figure 31 Illustration of the receptor regions developed by Oleg Travnikov and based on the GLEMOS modeling.

Populations who regularly and frequently consume large amounts of fish are more highly exposed to methylmercury. According to the European Commission, most people in central and northern Europe show bio indicators of exposure below internationally accepted safe levels for methylmercury. However, most people in coastal areas of Mediterranean countries, and around 1-5% of the population in central and northern Europe, are around these levels, and large numbers among Mediterranean fishing communities and the Arctic population exceed them significantly (EC, 2005). Even though it can be claimed that the ingestion dose of methylmercury becomes more uniform worldwide because of the wide international trading of fish, it is in this thesis further assumed that most populations are trading and eating fish within the same region of the world as the fish is caught, which is a simple assumption.

Introduction of measures leading to a reduction in emissions to the environment is expected to have a positively impact on human health and the environment. The pathway of mercury through the environment, however, is very complex and requires very complex modeling. In general are economic damage cost estimates based on the external costs associated with measurable damages to human health. The costs of human health damages presented in this thesis are directly related to the dose of methylmercury received through the ingestion of polluted food during pregnancy that links to effects on the developing fetuses. The effects have shown to result in changes in the child"s IQ. Reduced IQ can have a future negative economical impact through reduced job attainment and performance, as well as educational achievement, which, in turn affects earnings.

A literature review based on studies conducted in the USA which related costs on IQ decrement was performed by Spadaro and Rabl (2008). They concluded on the basis of this literature review that it is proper to use €12,000 (US$18,000) per IQ point. To estimate a worldwide average cost of damage per kg of mercury emitted due to ingestion, the method links statistics on country specific population and birth rates (i.e. the fraction of the population affected), to the slope factor and cost of IQ decrement (see Spadaro and Rabl (2008) for more information). The US costs based on the IQ decrement is adjusted by transferring the country specific cost to other countries using the Gross Domestic Product (GDP) per capita expressed as Purchasing Power Parity (PPP) as a weighting factor. Data on GDPppp per capita were for this thesis collected from The World Bank`s World Developing Index database, (2005) supported with data from the Central Intelligence Agency‛s` World Fact book, (2008) and the International Monetary Fund`s World Economic Outlook database, (2005). Information on population numbers and birth rates was collected from the United Nations Population division, (2005) while world population prospects for the year 2020 was collected from United Nations Population division, (2010). For a dose threshold of 6.7 µg/day of MeHg per person, the global average estimate (in 2010 € currency) for the year 2020 was about € 1700 (US$2200) per kg mercury emitted whilst € 3800 (US$ 5000) for 0 threshold.

5.6.2 Economic benefits from reduced damage costs in 2020

Economic benefits are estimated as the difference between the costs of IQ decrements determined for the 2005 emission situation and the costs of damages of IQ decrements determined for the reduced emission levels estimated under the Baseline 2020. A separate estimate is conducted on the alternative control scenario (i.e. introducing ACI techniques to the coal combustion sector). Table 8 illustrates the economic benefits from reduced impacts on IQ decrement resulting from the reduced mercury emissions under the Baseline scenario.

Table 8 **Economic benefits under the 2020 Baseline scenario compared to the 2005 situation.**

	Economic benefits in 2020 (in million (2010) €)	
	Threshold dose: 6.7 µg/day	**Threshold dose: 0 µg/day**
EU 27 / (Europe[1])	4.4/ (5.5)	10.0 / (12.4)
Asia[1]	3.6	8.1
Africa	0.9	2.1
South America	0.5	1.2
North America	1.8	4.1
Oceania	0.09	0.2
Total	**12.3**	**28.2**

[1] Includes 50% of Russian economic benefits.

The global costs of damages resulting from ingestion of methylmercury emitted in the EU 27 region in 2005 are ranging from € 22.7 million and € 52.0 million under the two assumptions on threshold dose. Only € 8.6 million (6.7 µg/day threshold dose) or € 19.8 million (0 µg/day threshold dose) of these damage costs were occurring in the EU 27. Large economic damage costs were thus also occurring outside the EU region. The estimated global benefits of an emission level in 2020 corresponding to the 2020 Baseline emission scenario are ranging from € 12.3 million to € 28.2 million under the two assumptions on threshold dose.

Economic benefits for the technology alternative of fully introducing ACI in electric utilities are displayed in Table 9.

Table 9 Economic benefits for the 2020 technology alternative of fully introducing ACI in electric utilities.

	Economic benefits in 2020 (in million (2010) €)	
	Threshold dose: 6.7 µg/day	**Threshold dose: 0 µg/day**
EU 27 / (Europe[1])	2.3 / (2.9)	5.3 / (6.5)
Asia[1]	1.9	4.3
Africa	0.5	1.1
South America	0.3	0.7
North America	1.0	2.2
Oceania	0.05	0.1
Total	**6.5**	**14.9**

[1] Includes 50% of Russian economic benefits.

The estimated global benefits of fully introducing ACI in electric utilities and the subsequent reductions in ingestion of methylmercury in the EU are ranging from 6.5 to 14.9 million (2010) € under the two assumptions on threshold dose.

Due to limited information in the literature, economic benefits from reducing severe exposure of methylmercury and the elevated risks of cardiovascular diseases, reproductive outcomes, immune systems effects as well as risks for premature death are not included in this analysis, -nor are the potentially environmental impacts. Most of the existing studies dealing with these benefits are locally oriented and it is difficult to extrapolate these results to a large regional scale. Sundseth et al., (2010), however, indicated on the basis of a case study on human health benefits (Rae and Graham, 2004) as well as a willingness-to-pay study for a healthier environment (Hagen et al., 1999) several times higher estimate if these endpoints were included in the analysis.

5.7 Step 6 – Selection of the best solutions

5.7.1 Input for implementation of policy

The investigated Baseline scenario indicates that emissions of mercury as a trace contaminant in fuels and minerals (primary anthropogenic emission sources) are becoming increasingly important to the environmental concentrations in EU compared to emissions from mercury used intentionally e.g. in products (secondary anthropogenic sources). High temperature processes like stationary combustion of coal, associated with energy or heat production in major power plants, small industrial or residential heating units as well as in various industrial processes, were the largest source categories of mercury emissions in 2005 and is also expected to be maintained under the Baseline scenario. Demonstrated results from the decision support system therefore suggests that additional future control strategies in the EU should be targeted industrial sources (which are so far not, or insufficiently, regulated at EU level) and safe treatment of mercury- containing wastes, waste water effluents, as well as residues collected from various combustion processes. Costs and benefits of such actions remain to be investigated.

In the alternative scenario, the cost of 100 % implementation of a sorbent based technology in the EU, such as ACI, severely outweighs the benefits of the resulting mercury removal. The annual cost of introducing ACI to the remaining half of the coal combustion facilities in the EU (covering about 115 000 MWe) would lead to an annual cost of about € 4.5 billion, which significantly exceeds the prospected annual benefits estimated in the range of € 6.5- 14.9 million (if focusing merely on the effects of IQ decrements). To justify introduction of sorbent technology for mercury specific removal in coal combustion facilities in the EU, the installation and operational costs need to be lowered drastically. According to NETL research activities sponsored by the US Department of Energy (DOE), the costs of sorbent injection for mercury removal have shown significant advances along with the potential for reductions in overall installation and operational costs. A DOE economic analysis released in 2007 indicates that the cost of mercury control could be drastically lowered compared to original estimates due to a reduction in the injection rate of a sorbent when using more efficient treated sorbents, and even offsetting the higher costs of the treated sorbents. The analysis indicated that a cost of 90 % mercury emission control by means of activated carbon injection ranged from about $30,000 to less than $10,000 per pound (equal to $22,000 to $66,000 /kg) of mercury removed for DOE field testing sites (Feeley et al., 2008). These DOE tests sites used a chemically-treated (brominated) activated carbon. Generally, brominated carbon affords much lower injection rates (mass sorbent/flue gas flow) than the untreated carbon to accomplish the same level of mercury removal. Thus, despite the fact that chemically treated carbons are more expensive than untreated ones, the use of chemically treated carbons allows to significantly lower the cost of mercury removal. It is important to have in mind, however, that fly ash captured from air pollution control devices can potentially be reused for engineering applications and has an economic value. Adding absorbents like activated carbon can affect the quality of the fly ash (and gypsum) and potentially prevent sales. Mercury control costs are therefore also affected by a potential loss of revenue for plants that sell their fly ash for beneficial reuse.

It is evident that large economic benefits can be achieved with reduced mercury emissions in the EU region. The investigated Baseline scenario implications highlight the importance of full implementation of existing measures by EU member states and the importance of making further progress on reducing mercury emissions from European sources. The EU legislations and directives such as the actions to reduce mercury emissions adopted under the LRTAP Convention, including agreements to meet the IPCC Kyoto targets on reduction on greenhouse gases will significantly contribute to such benefits. Since mercury emissions potentially are long- range transported, emission reductions in the EU region will also lead to reduced damage costs in other regions of the world. This is of particular interest when it comes to the elevated mercury levels observed e.g. in the Arctic. At the same time emissions occurring in other regions of the world are causing damage costs to the EU region. It can be claimed that the level of human and environmental exposure in the EU cannot be reduced to an acceptable level through domestic measures only and it should therefore be of EUs interest to lower both European as well as global mercury emissions. Since marginal costs per kg mercury abated probably are lower in developing countries, reducing emissions in these countries might be more cost- effective than reducing emissions domestically, which reconfirms the need for a global convention on mercury.

5.7.2 Data quality

The overall data quality ranking for the demonstrated framework is assumed as (B)[13] for the technology cost data, while (C)[14] for the benefit assessment (see footnote 13 and 14 or box 7 for explanations). In being iterative in each step, data and assessments achieved from the framework are constantly improved and uncertainties reduced as it is being applied or when new scientific information becomes available.

From the SFA it was found that knowledge on flows and emission sources on a large geographical scale is limited due to a lack of information on emission factors from various industrial processes and waste systems, especially for the mercury being discharges to water and land. Further developed and more advanced management and reporting strategies for industrial emissions is therefore advised, - highlighting a need for a larger degree of transparency and openness of information concerning production and use of mercury as well as from the use of raw materials containing mercury. Lack of

[13] B: An estimate based on significant amount of information representative of most situations and for which most of the background information is known.

[14] C: An estimate based on limited amount of information representative of some situations and for which background assumptions are limited.

information prevents the assessment of emission source, main flow paths, and thus the assessment of risks and the development of cost- efficient control strategies.

Uncertainty ranges for emission factors are difficult to obtain, since they are based on measurements conducted under particular conditions assumed to be typical. Measurements depend on the type of plant, and the maintenance, size, and age which is site- and country- specific. Uncertainty ranges is assumed in the order of 20-60% for emissions to air, while 50-100% for emissions to water and soil.

Indicative uncertainty ranges on activity data derived from statistics (including energy statistics, economic production rates, and population data) are presented in the EMEP/CORINAIR, (2007) Emission Inventory Guidebook. They propose that official data should not have any uncertainties attributed, while they for IEA energy statistics propose an uncertainty of 2-3% for OECD- countries whilst 5-10% for non-OECD countries.

Reproduction of mercury concentrations in ambient air from atmospheric modeling in this work does not exceed the modeling uncertainty requirements of 15-20%. Simulated total depositions is much higher – a factor of two. Spadaro and Rabl, (2008) identified in a 68% confidence interval a standard deviation of 4.2 for their emission (damage) cost estimate.

US EPA, (2005) reports an uncertainty range in the technology cost data in the order of -30 to +80 %. Typically, costs of technologies that are in the early phase of implementation will decrease over time. Costs are also highly site-specific, so they are normally presented as indicative costs collated from a range of literature being reported for different plant sizes and sites, which makes extrapolation to other plants less certain.

6 Conclusions

There is enough information available (in the literature and from the candidate works) that a decision support tool needed for introduction of cost- effective abatement of mercury can be developed.

- This thesis has provided and demonstrated a novel framework for a decision support system towards environmental policy on mercury in Europe (EU 27). Already existing knowledge and methods have been organized and linked to a set of a decision support system that has proven to facilitate a systematic and comprehensive assessment of the relevant costs and benefits of mercury emission reduction measures. This allows for it being practical and widely used.

We are in the state that we can provide policy makers a decision support tool that would allow for cost- effective solutions.

- The framework described in this thesis can be used to help identifying the main source categories, flows and environmental endpoints of contaminants as well as the production systems and consumption structures in the society causing these flows. It also helps addressing the current and future environmental problems and how they can be reduced in the most beneficial and effective way. By recommending a systems analysis approach, the study has enabled a holistic, multidisciplinary approach that can be used e.g. to assist the EU to take an informed and influential position in negotiations on the development of UNEP measures on mercury.

It is possible to assess economic benefits and compare these to costs of introducing the relevant measures.

- Recent scientific advancement allows for more relevant information, accurate assessments and reduced uncertainty as well as a more complete picture of the mercury problems and solutions to the problems. Several studies have been conducted on emission sources and the behavior of mercury in the environment and its environmental and economic consequences associated with its presence, which lead to a better basis for informed decision making. Information on costs of introducing relevant measures has also advanced. Uncertainties should be further reduced through obtaining more information from the scientific community, national experts, industry representatives and other stakeholders.

7 Recommendations

- Further development of the framework for the decision support system and the associated tools would be beneficial for the continued work on developing environmental policies for protection of human health and environment.
- Accurate data and associated information concerning the sources of emissions of mercury, especially in products and processes, and the economic costs and benefits of the alternative policy options that might control and reduce the risks associated with mercury in the environment is relevant as it could be featured in the global legally binding instrument that currently is under negotiation within UNEP. A significant outcome from applying the framework developed in this thesis could thus be a set of structured recommendations as to what action negotiators might take in order to allow for the most cost-effective measures as a whole.
- National and regional efforts to reduce environmental mercury concentrations need to be complemented, which in turn requires enhanced international coordination on data collection. International processes for harmonizing and exchanging knowledge between different scientific communities, chemicals directives and international programs and conventions, should therefore be promoted. Information can besides be reinforced in the framework of various international programs (i.e. UNEP) and conventions (i.e., UN ECE LRTAP, OSPARCOM, and HELCOM).
- The decision support system should be supported by best available scientific advancements and information, including information being made available to the processes in upcoming or existing international agreements such as those under the UNEP negotiations and the EU ECE LRTAP Convention. Co- operative programmes such as the EMAP (Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) can regularly provide governments and subsidiary bodies with qualified scientific information to support the development and further evaluation of the international protocols on emission reductions negotiated within the Convention. Such programmes (e.g. the EMEP programme) is carried out in collaboration with a broad network of scientists and national experts that contribute to the systematic collection, analysis and reporting of emission data, measurement data and integrated assessment results.
- Validation of results from mercury emission reductions on regional and global scale should be improved by implementing regular monitoring in air and water. Development of a coordinated global observation system for mercury is proposed in the EU GMOS project where high quality data for the validation and application of regional and global scale atmospheric models is proposed to give a firm basis for future policy development and implementation.

- Transparency in information on production, use, emissions, and costs could be facilitated by harmonizing and exchanging knowledge between different chemicals directives (e.g. the REACH directive) and international conventions, but should also include the industrial sector as well as other relevant stakeholders. Strengthening the links between research, industry and policy communities would improve the availability of existing environmental data for policy implementation purposes.

ABSTRACT

There is clear evidence from the global mercury cycle that there is an urgent need for actions to reduce global anthropogenic mercury emissions. A legally- binding global agreement to reduce emissions of mercury is soon in place, meaning that many countries need to take steps to lower their emissions. Identification and assessment of policy options that already are in place as well as setting pollution control objectives and development of effective strategies to meet these objectives are depending on a decision support tool that allow for identifying current and future environmental problems and to reduce these problems by providing a holistic management approach. Recent scientific advancement allows for more relevant information, accurate assessments and reduced uncertainty as well as a more complete picture of the mercury problems and solutions to the problems. Such information is of outmost interest when it comes to justifying spending resources on relevant measures. To make sure that resource allocation is favoring human welfare, the economic costs of introducing these measures need to be compared to the economic benefits.

The major goal of this study was to provide a novel combination of assessment tools that forms a framework for a decision support system towards environmental policy on mercury in Europe. The decision support tool was intended to act as a guideline for policy makers for the purpose of introducing cost- effective abatement of mercury. The framework for a decision support system was successfully demonstrated for the EU 27 countries.

It was for the EU 27 countries demonstrated that large economic benefits can be achieved globally with reduced mercury emissions in the EU region. The investigated Baseline scenario thus highlighted the importance of full implementation of existing measures and the importance of making further progress in reducing mercury emissions from European sources. The cost- benefit analysis, however, indicated that the economic cost of an alternative technological option for coal combustion in power plants and industrial boilers in the EU exceeds the economic benefits. Reducing emissions in developing countries may be more cost effective, which basically reconfirms the need for a global convention on mercury.

ABSTRACT (IN POLISH)

W ostatnich latach wiele uwagi poświęca się problematyce dotyczącej globalnego rozprzestrzeniania się związków rtęci w środowisku oraz działaniom na rzecz zmniejszenia antropogenicznych źródeł emisji tego pierwiastka. W chwili obecnej trwają przygotowania do wprowadzenia prawnie wiążącego globalnego porozumienia na rzecz zmniejszenia emisji związków rtęci, co wiąże się z podjęciem odpowiednich działań na poziomie międzynarodowym. Dotychczasowe badania naukowe obrazują skalę i sposoby rozwiązywania problemów związanych z redukcją emisji związków rtęci, uzasadniając przy tym wysokość wydatków niezbędnych na ten cel. Ekonomiczne koszty wprowadzenia środków ograniczających emisję związków rtęci powinny być porównywalne w stosunku do korzyści ekonomicznych osiągniętych w wyniku ich wdrażania.

Nadrzędnym celem rozprawy doktorskiej było stworzenie narzędzi, umożliwiających wdrożenie jednolitego systemu oceny oraz wspomagania decyzji w ramach wspólnej polityki środowiskowej Europy w sprawie rtęci. Określono korzyści ekonomiczne, jakie mogą być osiągnięte w skali globalnej poprzez redukcję emisji rtęci na obszarze Unii Europejskiej. Na podstawie opracowania (wyników) scenariusza bazowego, podkreślono znaczenie pełnego wdrożenia istniejących środków i dalszych postępów redukcji emisji związków rtęci przez państwa członkowskie UE.

Analiza kosztów i korzyści wskazuje, że koszty poniesione w wyniku zastosowania alternatywnego rozwiązania technologicznego podczas spalania węgla w elektrowniach i kotłach przemysłowych w krajach UE przewyższają korzyści ekonomiczne.

W krajach rozwijających się możliwości ograniczenia emisji związków rtęci mogą być ekonomicznie korzystne i potwierdzać założenia światowej konwencji w sprawie tego pierwiastka.

W ramach procesu wsparcia decyzyjnego, bardziej zaawansowanej formy zarządzania oraz raportowania poziomu realizacji strategii redukcji emisji przemysłowych; niezbędne jest wykorzystanie danych statystycznych na temat zastosowań tego pierwiastka oraz znajomość wartości współczynników emisji pochodzących z różnych procesów przemysłowych i składowisk odpadów, by możliwość przedostania się związków rtęci do wody i gleby była w jak największym stopniu ograniczona.

APPENDIX

Existing regulations and directives on mercury

As an executive body of the European Union the European Commission is responsible for proposing legislation which is presented to the European Parliament and Council for approval. Regulations are immediately enforceable as law in all member states simultaneously, whereas Directives require member states to achieve a result through their own procedures and legislative instruments. Within the EU there are a number of legislative acts which make reference to mercury. Existing regulations and directives on mercury is presented below:

Table A 1 An overview of EU regulations and directives on mercury emissions

Regulations	
Regulation (EC) No 1907/2006; amended by Regulation (EC) No 552/2009	The Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation bans the sale of mercury-containing measuring devices (e.g. manometers, barometers, sphygmomanometers, thermometers).
Regulation (EC) No 689/2008	Establishes prior informed consent (PIC) concerning the export and import of mercury compounds.
Regulation (EC) No 1102/2008	Bans the export of metallic mercury and certain mercury compounds and mixtures and concerns the safe storage of redundant metallic mercury.
Directives	
Directive 82/176/EEC	Sets limit values and quality objectives for mercury discharges by the chlor-alkali electrolysis industry.
Directive 84/156/EEC	Sets limit values and quality objectives for mercury discharges by sectors other than the chlor-alkali electrolysis industry.
Directive 89/369/EEC	On the prevention of mercury pollution from new municipal waste incineration plants.
Directive 89/677/EEC	Places restrictions on the marketing and use of certain dangerous substances and preparations e.g. anti-fouling paints containing mercury.
Directive 91/188/EEC	Prohibits the placing on the market and use of plant protection products containing certain substances such as mercury.
Directive 99/31/EC	On the landfill of waste containing mercury compounds.
Directive 2000/53/EC	Bans mercury in materials and components of vehicles.
Directive 2000/60/EC	Establishes a framework for Community action in the field of water policy (Water Framework Directive) which incorporates mercury discharge limits.
Directive 2002/95/EC	An annex to the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS Directive) significantly reduces the limit values for mercury in light bulbs.
Directive 2002/96/EC	The Directive on waste electrical and electronic equipment (WEEE) sets provisions for collection and treatment of light bulbs.
Directive 2006/66/EC	stipulates the maximum allowed content of mercury in batteries and accumulators and waste batteries and accumulators

Regulations	
Directive 2007/51/EC	Relates to restrictions on the marketing of certain measuring devices containing mercury.
Directive 2008/1/EC	Integrated Pollution Prevention and Control (IPPC) is a key legal instrument for reducing mercury emissions.
Directive 2008/98/EC	Amalgam from dental waste is characterized as hazardous so subject to the Waste Framework Directive.
Directive 2008/105/EC	Stipulates environmental quality standards in the field of water policy for certain priority substances including mercury and its compounds.
Directive 2009/161/EU	Establishes a list of indicative occupational exposure limit values for workers who may be exposed to mercury.

Table A 2 An overview of mercury policy

Reduction of Hg emissions			
European	UNECE-LRTAP TF Convention on Long-Range Transboundary Air Pollution	1979	Legally binding instrument to deal with problems of air pollution on abroad regional basis • Aims to cut emissions of Hg from industry, combustion and waste and lower emissions from products http://www.unece.org/env/lrtap/welcome.html
	OSPAR Convention for the protection of the Marine Environment of the North-East Atlantic	1998	Started as Oslo convention against dumping from ships/aircraft in 1972. Aims to reduce marine Hg concentrations to near background levels and cease discharges, emission and losses by 2020 Includes specific decisions/recommendations covering: • Chloralkali plants • Pollution from Hg products • Release from dentistry • Release from crematoria (in the UK a burden sharing scheme, CAMEO, aims to achieve a 50 % reduction in Hg emissions from this source) http://www.ospar.org/
	Barcelona Convention	1976	Part of the Convention for the Protection of the Mediterranean Sea Against Pollution • Goal is reduction of pollutants transported to the Mediterranean sea http://www.unepmap.org/index.php?module=content2&catid=001001004
	Water Framework Directive	2000	Integrated river basin management for Europe • Covers water in lakes, streams, rivers, estuaries, coasts and Aquifers • Aims to achieve good water quality in terms of chemistry and ecology • Mercury is one the “priority hazardous substances” which should be phased out from EU waters by 2020 http://ec.europa.eu/environment/water/water-framework/index_en.html
Baltic Region	HELCOM Declaration on the	1988	Reduce Hg discharges to the Baltic sea • Initial aim was a 50 % reduction by 1995 – while this target was not met since then a number of binding recommendations have

Reduction of Hg emissions			
	Protection of the Marine Environment of the Baltic Sea Area		been introduced to work towards lowering Hg emissions http://ec.europa.eu/environment/water/marine/helcom.htm
Transport/Storage of Hg			
European	Mercury export ban and its safe storage	2008	• Obligation to store mercury waste "in a way that is safe for human health and the environment" before eventually being disposed of. • Export ban on elemental Hg, other mercury compounds as e.g. cinnabar ore, mercury chloride and mercury oxide. • Compounds for research and development, medical or analytical analysis purposes are not covered by the prohibition. http://www.europarl.europa.eu/sides/getDoc.do?language=en&type=I M-PRESS&reference=20080520IPR29477
	Integrated pollution prevention and control: (IPPC) Directive	2008	Permit system for industry and agriculture http://ec.europa.eu/environment/air/pollutants/stationary/ippc/index.ht m
	European Pollutant Release and Transfer Register (EPRTR)	2006	Register for the use and release of Hg. • Publicly accessible electronic database http://prtr.ec.europa.eu/
International	Basel Convention on the Control of Transboundary Movements of hazardous Wastes and their Disposal	1992	Aims to protect health and environment from use/movement of waste to developing countries/eastern Europe • Hg contaminated waste may not be exported from the EU or OECD for disposal, recovery or recycling in other countries. http://www.basel.int/
	Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade	2004	Prevents the export of specified chemicals and pesticides cannot take place without prior informed consent of the importing country • At present this procedure covers mercury compounds used as pesticides, but mercury and its compounds intended for industrial use are not. http://www.pic.int/home.php?type=s&id=77
Products			
European	Mercury From Chloroalkali Process Directive	1982	Includes a number of daughter directives to limit emissions from mercury chloralkali cells. http://eurlex. europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31982L0176:EN:HTML
	Hazardous waste directive	1991	States that where the discharges of hazardous waste take place, the waste shall be recorded and identified http://ec.europa.eu/environment/waste/hazardous_index.htm

Reduction of Hg emissions			
	91/689/EEC		
	Directive 2006/66/EC on batteries and accumulators	200 6	Limit the amount of Hg permissible in batteries to 0.0005 % by weight or 2 % by weight for button cells http://ec.europa.eu/environment/waste/batteries/index.htm
	Directive 94/62/EC on Packaging and packaging waste	199 4	Limits amount of mercury in packaging http://www.speciation.net/Database/Links/European-Legislation-Council-Directive-9462EC-on-Packaging-and-packaging-waste-;i1808
	End of life vehicles (ELV) directive (2000/53/EC)	200 0	Restricts the use of mercury in vehicles on sale after 2003 http://ec.europa.eu/environment/waste/elv_index.htm
	Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (2002/95/EC)	200 2	Restricts use of Hg in electrical and electronic equipment from 2006 Exceptions for certain lamps http://eurlex. europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32002L0095:en:HTML
	Waste electrical and electronic equipment (WEEE) directive (2002/96/EC)	200 2	WEEE must be treated with the best available treatment and recycling techniques components of electronic goods such as mercury containing switches must be removed from WEEE and Hg must be removed from gas discharge lamps http://eurlex. europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32002L0096:en:HTML http://ec.europa.eu/environment/waste/weee/index_en.htm

Anthropogenic emissions to the atmosphere from the EU 27 countries

Table A 3 Overview of the anthropogenic emissions to the atmosphere to air, presented by country.

Country	PPs&District Heating conventional thermal electricity and heat generation (on coal and oil)	Residential	Cement Production	Metal Production	Chlorine Production Using Hg Method	Waste	Other	TOTAL
Austria	0,19	0,18	0,11	0,66	0,00	0,02	0,03	1,20
Belgium	1,12	0,23	0,56	0,44	0,27	0,06	0,27	2,95
Bulgaria	1,47	0,00	0,13	2,45	0,00	0,00	0,00	4,05
Cyprus	0,01	0,00	0,14	0,00	0,00	0,00	0,00	0,16
Czech Republic	1,93	0,00	0,13	0,62	0,00	0,07	0,10	2,85
Denmark	0,72	0,00	0,04	0,00	0,00	0,07	0,03	0,86
Estonia	0,50	0,02	0,01	0,00	0,00	0,00	0,00	0,53
Finland	0,19	0,02	0,02	0,35	0,07	0,00	0,20	0,85
France	4,62	0,17	0,55	0,62	0,82	1,20	0,79	8,77
Germany	5,18	2,52	1,98	4,88	0,94	3,49	1,19	20,17
Greece	0,93	0,66	1,04	0,07	0,08	0,01	0,42	3,19
Hungary	0,66	0,62	0,22	0,20	0,00	0,96	0,09	2,74
Ireland	0,09	0,09	0,27	0,00	0,00	0,03	0,03	0,50
Italy	3,97	1,35	3,09	2,48	1,30	0,68	0,00	12,88
Latvia	0,10	0,00	0,05	0,00	0,00	0,00	0,00	0,15
Lithuania	0,29	0,42	0,16	0,00	0,00	0,00	0,04	0,90
Luxembourg	0,01	0,00	0,01	0,45	0,00	0,00	0,00	0,47
The Netherlands	0,21	0,00	0,16	0,21	0,04	0,12	0,00	0,73
Poland	6,89	0,83	1,42	1,82	0,36	0,05	1,96	13,32
Portugal	1,34	0,39	0,52	0,06	0,00	0,98	0,07	3,36
Romania	2,39	0,00	1,05	0,28	0,00	0,89	0,01	4,63
Slovakia	1,09	1,09	0,27	0,27	0,11	0,08	1,62	4,53
Slovenia	0,30	0,00	0,02	0,10	0,00	0,00	0,00	0,41
Spain	4,84	0,06	3,51	0,90	0,61	0,16	0,10	10,18
Sweden	0,17	0,02	0,02	0,45	0,04	0,12	0,03	0,85
United Kingdom	1,86	0,00	0,20	0,54	1,32	0,17	0,06	4,15
Malta	0,59	0,00	0,00	0,00	0,00	0,03	0,00	0,62
EU 27	**41,66**	**8,67**	**15,67**	**17,84**	**5,95**	**9,17**	**5,12**	**106,02**

The Stock- Flow model approach

Emissions generated from the „secondary anthropogenic emission"- category can be estimated by linking information on consumption of various mercury- containing products (S) to the methodology described in (Kindbom and Munthe, 2007), i.e. using distribution factors (D) to allocate the mercury-containing products into different waste treatment categories and subsequent attribute to them atmospheric emission factors on breakage, metal scrap smelting, waste incineration and land-filling. (See Kindbom and Munthe, 2007 for complementary information). The methodology can be summarized in equation (1).

$$M_{Air,Water,Land} = S * D * EmF_{Air,Water,Land}$$

A Stock-Flow model approach (e.g. Muller , 2006), originally developed to simultaneously forecast resource demand (inputs) and waste generation (outputs), can be applied for developing future projections on emissions, discharges and releases from mercury used intentionally in products, whilst at the same time accounting for the mercury accumulated in society/economy. The basic model assumptions are driven by physical and economic determinants, such as regulative changes or substitution effects which in turn, affect the demand of mercury embodied in products. This in turn, induces a push of emissions or waste over a certain lifetime whilst mercury stocks are accumulated and generated in the system. The basic assumptions based on the model presented in Muller, (2006) are described by equation (2)-(7).

$$\frac{dS(t)}{dt} = \frac{S_{in}(t)}{dt} - \frac{S_{out}(t)}{dt}$$

$$\frac{dM(t)}{dt} = \frac{M_{in}(t)}{dt} - \frac{M_{out}(t)}{dt}$$

Equation (2) is the balance equation of products containing mercury (S) whilst equation (3) describes the general mass balance of mercury (M). With time, the input to the production systems/economy equals the output.

$$S(t) = POP(t)$$

The driver for the demand of mercury (M) and products containing mercury (S) is by equation (4) described as changes of population (POP). This is however, a very simple assumption not taking into account economic variables such as prices or market elasticity.

$$\frac{S_{out}(t)}{dt} = \int L(t,t') * \frac{S_{in}(t')}{dt} * dt'$$

Equation (5) represents the lifetime parameter (L) which imply that the mercury or product consumed at time (t`) is leaving the production systems/economy at time (t).

$$\frac{M_{in}(t)}{dt} = \frac{S_{in}(t)}{dt} * M_s(t)$$

The input to the substance stocks of mercury (M) in the society, which depends on the drivers in the system (equation (4) as well as the concentrations of mercury (Ms) associated with (S), is described by equation (6).

$$\frac{M_{out}(t)}{dt} = \int L(t,t') * \frac{M_{in}(t)}{dt} * dt'$$

Equation (7) illustrates the mercury substitution effects (only inputs), e.g. changes of concentrations in products. The substitution effect is typically driven from regulatory effects related to the use of mercury in products.

(dS/dt) and (dM/dt) – Net stock accumulation.

(Sin/dt) and (Min/dt) – System inputs.

(Sout/dt) and (Mout/dt) – System outputs.

Emission factors

Table A 4 Emission factors for mercury, used to estimate the 2005 emissions.

Category	Unit	Emission factor
Coal combustion	g/tonne coal	
Power plants		0.1–0.3
Residential and commercial boilers		0.3
Oil combustion	g/tonne oil	0.001
Non-ferrous metal production		
Copper smelters	g/tonne Cu produced	5.0
Lead smelters	g/tonne Pb produced	3.0
Zinc smelters	g/tonne Zn produced	7.0
Cement production	g/tonne cement	0.1
Pig iron & steel production	g/tonne steel	0.04
Waste incineration	g/tonne wastes	
Municipal wastes		1.0
Sewage sludge wastes		5.0
Mercury production (primary)	kg/tonne ore mined	0.2
Gold production (large-scale)	g/g gold mined	0.025–0.027
Caustic soda production	g/tonne produced	2.5

The Spadaro and Rabl, (2008) methodology

The Spadaro 2008 study presents the first estimate of global average neurotoxic impacts and damage costs by defining a comprehensive transfer factor for ingestion of methyl-Hg, T_{av}, as ratio of global average dose rate, D_{av}, and global emission rate, E.

$$T_{av} = D_{av}/E \quad [(\mu g_{MeHg}/yr)/(kg_{Hg}/yr)].(1)$$

The product of the transfer factor and the ratio of molecular weights Hg/MeHg is the intake fraction that is the fraction of the emitted Hg that passes through a human body.

The slope factor (i.e. number of IQ point losses due to daily (yearly) intake of MeHg) of 0.036 IQ points per µg/day in their study is a product of the dose-response function for IQ loss per increase in maternal hair mercury, a ratio hair/cord blood, a ratio cord blood concentration and maternal blood concentration and a relation between intake dose of MeHg and concentration.

Quoting further Spadaro and Rabl, if a mother i has had ingestion dose of D_i, the lifetime impact I_i on the offspring is an IQ loss of

$$I_i = s_{DR} \cdot (D_i - D_{th}) \quad (2)$$

where D_{th} is the threshold dose.

If there are p persons in overall population, the average lifetime IQ loss per person can be expressed as

$$I_{av} = s_{DR} \cdot \frac{\sum_{i=p_{th}}^{p} (D_i - D_{th})}{p} \quad (3)$$

where p_{th} is the number of individuals with maternal dose below D_{th} and the rest $(p\text{-}p_{th})$ describes all individuals with maternal dose above the threshold dose. Let‟s further also rewrite the average dose above the threshold dose Dth, i.e. the second term in the eq. 20, by the term Dav(Dth).

Spadaro and Rabl then document corresponding IQ loss of 0.020 IQ points if Dth=6.7 µg/day and of 0.087 IQ points for zero threshold, i.e. Dth=0 µg/day.

Additional impact due to kg of emitted Hg should consider the rate at which new individuals are affected. The birth rate b and time interval during that the impact occurs – assuming reasonably that $\Delta t=1$ – enter into the model. Following the Spadaro and Rabl study, the marginal impact on IQpoints due to kg of emitted Hg can be calculated

$$\Delta I = p \cdot b \cdot \Delta t \cdot s_{DR} \cdot \Delta D_{av}(D_{th}) \tag{4}$$

To rewrite Dav(Dth) by

$$\left(\frac{1}{p} \cdot \sum_{i=p_{th}}^{p} D_i - \frac{p - p_{th}}{p} \cdot D_{th} \right)$$

...and multiply it by $\left(E \cdot T_{av} / D_{av}\right)$ which is equal to unity by its definition, one can express the increment in dose as

$$\Delta D_{av}(D_{th}) = \Delta E \cdot T_{av} \cdot \frac{1}{p \cdot D_{av}} \cdot \sum_{i=p_{th}}^{p} D_i \tag{5}$$

Inserting eq. 5 in eq. 4, one can derive the incremental impact due to ΔD/Δt kg of emitted mercury as follows

$$\Delta I = p \cdot b \cdot \Delta t \cdot s_{DR} \cdot \left(\Delta Q / \Delta t\right) \cdot T_{av} \cdot \frac{1}{p \cdot D_{av}} \cdot \sum_{i=p_{th}}^{p} D_i \tag{6}$$

Allowing the variation of the birth rates among populations – *k* regions or countries, the equation 6 for the unit of emission can be reformulated as

$$\Delta I = \sum_k \left(p_k \cdot b_k\right) \cdot s_{DR} \cdot T_{av} \cdot \frac{1}{p \cdot D_{av}} \cdot \sum_{i=p_{th}}^{p} D_i \tag{7}$$

The product of the (physical) impacts, i.e. IQpoint losses, and damage costs, COSTk, is total external costs due to unit of emission.

One can assume that emission and impact are simultaneous and occur during a certain time interval. Then, there is no adjustment required in the external costs calculation. However, the time (cessation) lag between a change in emission and the impact can be reasonably assumed. The formula for the external costs per unit of mercury emission can be rewritten as

$$\sum_k \left(p_k \cdot b_k \cdot COST_k\right) \cdot \beta^{lag} \cdot s_{DR} \cdot T_{av} \cdot \frac{1}{p \cdot D_{av}} \cdot \sum_{i=p_{th}}^{p} D_i \tag{8}$$

Work loss years can be calculated as

$$WLYs = \sum_k \left(p_k \cdot b_k\right) \cdot s_{DR} \cdot T_{av} \cdot \frac{1}{p \cdot D_{av}} \cdot \sum_{i=p_{th}}^{p} D_i \cdot \sum_{t=18}^{65} prob_t \cdot (PARTIP_t + EARN_t - EDU_t) \tag{9}$$

Where the probability of surviving in the year *i*, by *prob* keeping here *p* for the population.

Work loss years and damage costs in the recipient country r and in the year t after release of emission are

$$WLY_{rt} = p_r \cdot b_r \cdot s_{DR} \cdot T_{av} \cdot \frac{1}{p \cdot D_{av}} \cdot \sum_{i=p_{th}}^{p} D_i \cdot prob_j \cdot (PARTIP_j + EARN_j - EDU_j) \tag{10}$$

where j = (t-lag) and

$$COSTS_{rt} = WLY_{rt} \cdot LP_r \cdot (\beta_{rt} \cdot (1 + g_{rt}))^t + EDUEXP_r \cdot (\beta_{rt} \cdot (1 + e_{rt}))^t \tag{11}$$

where ($EDUEXP_r \cdot (\beta_{rt} \cdot (1 + e_{rt}))^t = 0$) if $t \neq (18+lag)$.

The products of eq. 10 and eq. 11 can enter into the E3ME model used also in the DROPS project (Deliverable D 6.2., http://drops.nilu.no), while the product of eq. 12 can be used directly in the cost-benefit analysis.

Total damage costs per unit of emission of mercury released now are then

$$COSTS = \sum_{r=1}^{41} \sum_{t=18}^{65} (WLY_{rt} \cdot LP_r + EDUEXP_r) \cdot (\beta(1+g))^{t+lag} \tag{12}$$

where $EDUEXP_r = 0$ if $t \neq 18$.

SCIENTIFIC ACHIEVEMENTS

SCIENTIFIC PAPERS (PEER- REVIEWED)

2012:

1. Sundseth, K., Pacyna, J.M., Pacyna, E.G., Panasiuk, D. 2012. Substance Flow Analysis of Mercury Affecting Water Quality in the European Union. *Water, Air, & Soil Pollution* 223 (Issue 1), p 429-442. DOI 10.1007/s11270-011-0871-0.

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1. Sundseth, K., Pacyna, J.M. Ny sensorteknologi for miljøovervåkning etter skipsulykker / New sensor technologies for environmental monitoring in water. Edited by Nyeggen, A. and Grossberndt S. NILU web January, 2012. Link: http://www.nilu.no/Nyhetsarkiv/tabid/74/NewsId/199/language/en-GB/Default.aspx.

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