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Socio-economic costs of continuing the status-quo of mercury pollution

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Summary

Mercury is released from a variety of sources including energy production, industrial applications as well as production, use and disposal of mercury-containing products. Coal combustion is the main source category. On the global scale, Asia contributes with more than 40% of the global emissions. Due to its chemical and physical characteristics, mercury is capable of global distribution via the atmosphere and many remote ecosystems have been affected by this toxic element.

Mercury exists in the environment in different forms, the most toxic being methyl mercury. This is also the form that bioaccumulates in aquatic food chains. Consumption of fish is thus one of the most important exposure pathways for humans. It has been concluded that a significant portion of humans and wildlife throughout the world are exposed to methyl mercury at levels of concern.

In a socio-economic perspective, mercury pollution results in costs to society including for example damage costs from negative impacts on human health and the environment, loss of income from reduced commercial fisheries, administrative costs for scientific research and development, control and risk communication.

The most serious human health impact of the global mercury pollution is neurological damage leading to impaired development of the brain, when exposure occurs in the pre-natal phase i.e. if pregnant women ingest food contaminated with methyl mercury. The impaired development of the brain leads to a loss of IQ (Intelligence Quotient) points. Other toxicological effects include increased risks for cardiovascular diseases. The damage costs to society induced by loss of IQ include e.g. loss of earnings and cost for loss of education.

In this study damage costs for human health impacts of mercury with respect to loss of IQ following consumption of contaminated fish have been assessed. The assessment was made for a Status Quo scenario where it was assumed that no further actions were taken to control mercury emissions in the period 2005 to 2020. The status quo scenario includes increases in economic growth and thus increased emissions of mercury from by-product sources, e.g. energy production and industrial processes. According to this scenario, mercury emissions will increase with about 25 % between 2005 and 2020 for both by-product sources and intentional use.

The annual damage costs for ingestion of methyl mercury was estimated to be approx. 8 *Billion* 2005 US$ for by-product emissions and 2 *Billion* 2005 US$ for emissions from intentional use of mercury in the SQ

scenario in 2020[1]. The corresponding damage cost for inhalation of mercury was estimated to be 2,9 *Million* 2005 US$ i.e. a small fraction of the costs associated with ingestion of contaminated fish. These results are valid for the global population in general. For some exposed population groups such as artisanal and small scale gold miners, exposure to mercury via inhalation may lead to more serious health impacts and consequently significant damage costs. The total damage costs to society of mercury pollution are likely to be considerably higher than the estimates presented here since the analysis was limited to costs related to loss of IQ and did not include other potential costs to society.

In addition to the SQ scenario, damage costs for two other scenarios developed in the UNEP report on Global Anthropogenic Emissions of Mercury (2008) were considered: the Extended Emission Control (EXEC) and the Maximum Feasible Technical Reduction (MFTR) scenarios. In these scenarios, higher degrees of emission control are assumed resulting in a decrease of total emissions of 50 % and 60 %, respectively in the period 2005-2020. The corresponding annual benefits of reduced damage costs were estimated to be around 5 and 6 *Billion* US$ for the EXEC and MFTR scenarios, respectively.

These estimates clearly indicate that large benefits can be achieved by reducing global mercury emissions. Co-benefits of multi-pollutant-controls, controlling not only mercury emissions but also e.g. particulate matters, SOx and NOx, are expected to be considerable in the case of e.g. coal combustion.

Mercury pollution can potentially affect populations all around the world. A wealth of information is available on contamination levels and potential impacts in remote environments in the Nordic countries, North America and the Arctic. Based on an evaluation of global fish consumption in combination with modelled global deposition patterns of mercury, Australia/Oceania, parts of South America and South East Asia were identified as additional regions with high potential risks for mercury impacts and thus damage costs of mercury pollution. It should be noted that this geographical assessment is based on risks associated with consumption of fish contaminated by long-range transport of mercury only. Other regions may be more severely affected by mercury exposure from e.g. artisanal gold mining and handling of toxic waste.

[1] Emissions from by-product sources and intentional use are treated separately since the abatement strategies for these two source categories are very different.

List of abbreviations and definitions

Word or abbreviation	Explanation/definition
Hg	Mercury
MeHg	Methyl mercury
By-product emissions	Defined as emissions from sources where mercury is present as a by-product or contaminant in fuel or raw material. Also includes other major point source categories such as mining of mercury and gold.
Emissions from intentional use	Defined as emissions of mercury from sources where mercury is intentionally used in industry or products.
Consumption	Used here when discussing emissions from products containing mercury. Defined as the amount of mercury used for a specific product category in the time and location where the product is sold i.e. not where the product is produced.
SQ Scenario	Status Quo. Scenario where no further action is taken to reduce mercury emissions. Economic and population growth leads to increased energy consumption and industrial production and thus increased mercury emissions.
EXEC Scenario	Extended Emission Control. Scenario where defined control measures to reduce mercury emissions are made. See Appendix 2 for further details.
MFTR Scenario	Maximum Feasible Technical Reduction. Scenario where in addition to the emission control in EXEC, mercury-specific control measures are applied. See Appendix 2 for further details.
ASGM	Artisanal and Small-scale Gold Mining. Mercury used to amalgamate gold in small-scale mining operations.
VCM	Vinyl Chloride Monomer production. Mercury (in the form of mercury chloride) used as catalyst in production of Vinyl Chloride Monomer
CA	Chlor-Alkali industry. Mercury used in electrochemical cell process for chlorine gas production
Batt	Battery. Mercury used in mercury oxide batteries and button cell batteries.
Dental	Dental amalgam. Mercury used in dental applications.
Meas	Measuring and control devices. Mercury in a range of different products including thermometers, barometers, manometers, etc
Light	Lamps. Mercury containing low energy lamps, fluorescent tubes etc.
Electr	Electrical and electronic devices. Switches, relays and other devices containing mercury.
Other	Other applications of mercury. Includes pesticides, fungicides, laboratory chemicals, in pharmaceuticals, as a preservative in paints, traditional medicine, cultural and ritual uses, cosmetics

Preface

Mercury is considered a global pollutant and it has been concluded that a significant portion of humans and wildlife throughout the world are exposed to methyl mercury at levels of concern. In 2007 the Governing Council of UNEP established an ad-hoc Open Ended Working Group (OEWG) to review and assess options for enhanced voluntary measures and international legal instruments for mercury. The results from the OEWG will be reported to the Governing Council in February 2009 with a view to decide on how to implement international long-term measures against mercury pollution.

Most of the measures needed to reduce emissions will lead to costs to society. However, mercury pollution also results in socio-economic costs. The aim of this report is to present an estimate of the socio-economic costs of continued mercury contamination of the environment as an input to the global considerations on what international long-term action should be taken.

A final draft of the report was presented and discussed at a seminar in connection to the second OEWG-meeting in October 2008 in Nairobi, Kenya. The final draft report was also submitted as an information document to the OEWG-meeting.

The study was funded by the Nordic Council of Ministers, the Norwegian Ministry of Environment and the Swedish Chemicals Agency. The development of the report was supervised by Petra Ekblom, the Swedish Chemicals Agency (lead), Henrik Eriksen and Anne Kathrine Arnesen, the Norwegian Ministry of Environment.

Valuable input during the development of the report was received from Lars Drake (the Swedish Chemicals Agency), Petra Hagström (the Swedish Environmental Protection Agency), Frank Jensen (the Danish Environmental Protection Agency) and Magnus Nyström (Finnish Environment Institute). An early draft was also reviewed by Patrik Söderholm, professor in economics at Luleå University of Technology, Sweden.

The study was performed by the Norwegian Institute for Air Research (NILU), Norway, IVL Swedish Environmental Research Institute, Sweden and NILU Polska, Poland.

1. Introduction

Mercury (Hg) is one of the most important environmental contaminants that need attention from policy makers, industry, and the general public in order to assess the extent of the problem and possible measures to reduce the negative impacts. This contaminant is toxic, persistent, and long-lived in the atmosphere and a subject of transport with air masses on intercontinental scale. Hg emitted in industrialised regions can be transported to other continents or to sensitive ecosystems in remote regions such as the Arctic (AMAP, 2002; UNEP, 2008). Coal combustion is the main source of Hg emissions to the atmosphere with contributions from e.g. industrial and mining/metal processing activities and waste management.

Given the global nature of Hg pollution, international agreements and cooperation are needed to cope with the problem of environment and human health impacts caused by Hg contamination. In preparation for such agreement, the UNEP Governing Council in 2001 commissioned the Global Mercury Assessment, which was completed in 2002. This assessment concluded that policy action on global scale could have significant effect on Hg levels in the environment. Furthermore, the UNEP Governing Council concluded in 2003 that there is enough evidence on significant global adverse impacts from Hg to warrant further international action to reduce the risks to humans and wildlife from the release of Hg. In 2005 and 2007, ministers and other government representatives from several countries met at the UNEP Governing Council to address the question of international action to reduce emissions of and human exposure to Hg on a global scale. In 2007 the Governing Council established an ad-hoc Open Ended Working Group (OEWG) to review and assess options for enhanced voluntary measures and international legal instruments for Hg. The results from the OEWG will be reported to the Governing Council in 2009 with a view to decide on how to implement international long-term measures against mercury pollution.

To develop cost-efficient strategies to reduce environmental and human health impacts of Hg, it is necessary to examine efficiencies and costs of available options to reduce emissions and exposure to Hg. A full societal cost benefit analysis would require detailed information on alternative strategies and associated costs of reducing emissions as well as quantitative source-receptor and dose-response descriptions and quantified economic benefits for reducing the impacts on human health and ecosystems. In this study we focus on assessing the costs of Hg pollution caused by negative impacts on human health if no further action is taken to reduce mercury emissions i.e. the costs of inaction, and to provide estimates of the potential benefits of reducing emissions world-wide.

The following specific objectives were defined in order to meet the main goal of this project:

- Presentation of a brief overview of Hg as a global pollutant, highlighting the major problems and risks.
- Review of available published information on damage costs of Hg pollution.
- Development of new estimates of damage costs relevant to the current level of Hg pollution based on available information from the literature and recent studies by the Contractor for the EU with some case study countries in focus.
- Attempt to extrapolate damage costs from case studies in the Czech Republic, Germany, Norway and Poland from recent EU projects to the regional/global level or to other relevant countries/regions.
- Assessment of the damage costs to society of continuing the status-quo of Hg pollution.
- Identification of countries/regions and/or (sub) populations that will bear the damage costs of the Hg pollution in the case of continuing Hg emissions.
- Development of conclusions to facilitate discussions and decision making at the OEWG of mitigating Hg pollution.

2. Overview of mercury as a global pollutant

Mercury is released to the atmosphere, aquatic environment, and directly to the terrestrial environment via waste, mine tailings etc. The assessment of atmospheric emissions is much more advanced and accurate than the assessment of Hg releases to the two other compartments of the environment. Atmospheric emissions are also responsible for the global distribution of Hg via air transport and are thus relevant for a global assessment.

2.1 Atmospheric emissions of mercury

Sources of mercury emissions

Atmospheric emissions of Hg occur during the production and consumption of industrial goods, waste disposal and as re-emission from aquatic and terrestrial surfaces. Production of energy and industrial goods is by far the largest source category of atmospheric emissions of Hg. Processing of mineral resources at high temperatures, such as combustion of fossil fuels, roasting and smelting of non-ferrous metal ores, coke production and iron and steel foundries, as well as kilns operations in cement industry emit most of the anthropogenic Hg to the atmosphere. A list of processes emitting the largest amounts of Hg to the atmosphere includes:

- combustion of coal in utility, industrial, commercial, and residential boilers,
- oil product combustion in utility, industrial, commercial, and residential boilers,
- cement production in wet and dry rotary kilns,
- primary and secondary production of non-ferrous metals,
- pig iron and steel production,
- Hg production,
- gold production, and
- waste incineration.

The use of Hg in industrial processes and products also cause emissions of Hg to the atmosphere. The use of Hg in products may give rise to emissions during the production phase as well as during use and disposal.

The major uses of Hg include:

- chlor-alkali production using the Hg cell process,
- vinyl chloride monomer (VCM) production,
- artisanal gold mining,
- amalgam use for dental services,
- Production, use and disposal of Hg in products including
  - batteries
  - measuring and control instruments
  - electrical lighting, wiring devices, and electrical switches

The almost exponential demand of electronic devices (highly correlated with economic growth) including Hg is giving a rise to a non negligible Hg use being 287 tonnes in 2004 (Widmer et al., 2005).

Global Hg consumption by application and region of the world in the year 2005 is presented in Figure 1. The largest consumers of Hg include artisanal gold mining (21 % of the total of 3798 tonnes used), VCM production (20 %), chlor-alkali production (13 %), and batteries production, dental applications, and measuring and control instrument production (each contributing to the total consumption with about 10 %). About a half of the consumption of Hg at present is assigned to the region of East and Southeast Asia (UNEP, 2008).

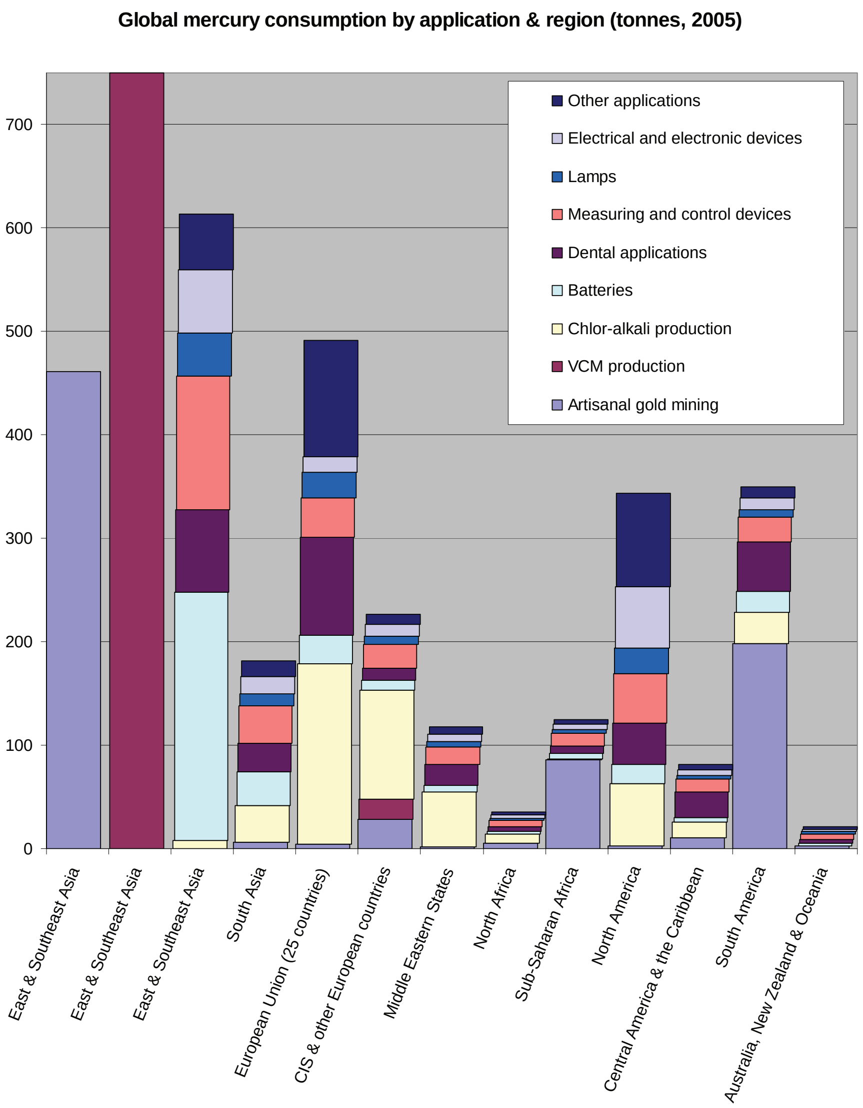

Figure 1: Global Hg consumption in the year 2005 (3798 tonnes) by application and by region (UNEP, 2008)

Atmospheric emissions of mercury in the year 2005

Atmospheric emissions of Hg from major sources (mentioned above) worldwide in the year 2005 were estimated within the UNEP Chemicals Global Mercury Assessment (GLOMER) project (UNEP, 2008). The results of these estimates are presented in Figure 2.

About three quarters of the total anthropogenic emissions of Hg in the year 2005 estimated to be 1958 tonnes comes from sources where Hg is emitted as a by-product i.e. sources where mercury is present as a contaminant in fuel or raw material, and the rest is emitted during various applications of Hg. The largest emissions of Hg to the global atmosphere occur from combustion of fossil fuels, mainly coal in utility, industrial, and residential boilers (almost 47 %), followed by artisanal and small-scale gold mining (almost 17 %), ferrous and non-ferrous metal production, including large-scale gold production (16 %) and cement production (about 9.5 %).

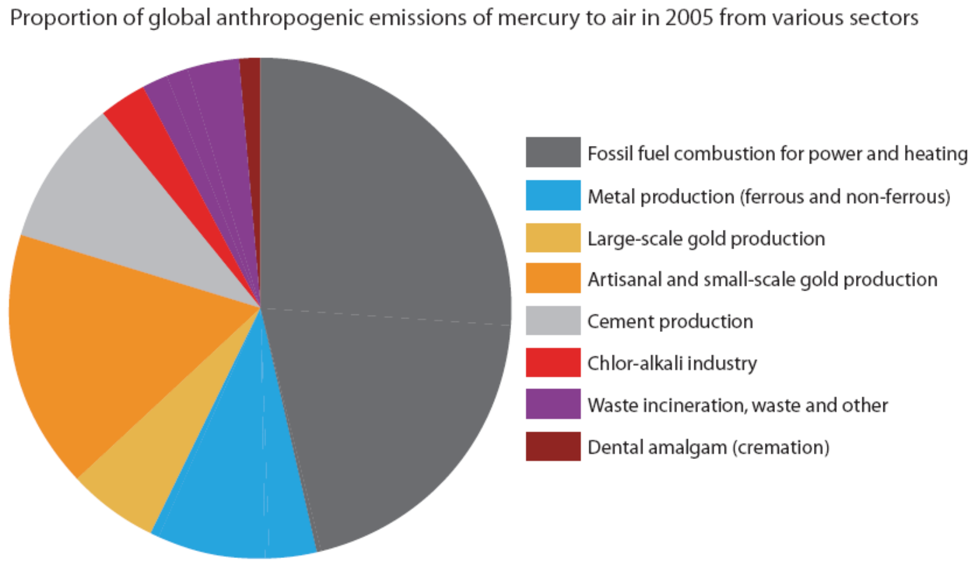

Figure 2: Global anthropogenic emissions of mercury to air in 2005 (1958 tonnes) from various sectors (UNEP, 2008)

Two thirds of the anthropogenic emissions of Hg in 2005 originated from sources in Asia. The contribution of the 2005 emissions from anthropogenic sources in various continents to the total emissions is presented in Figure 3

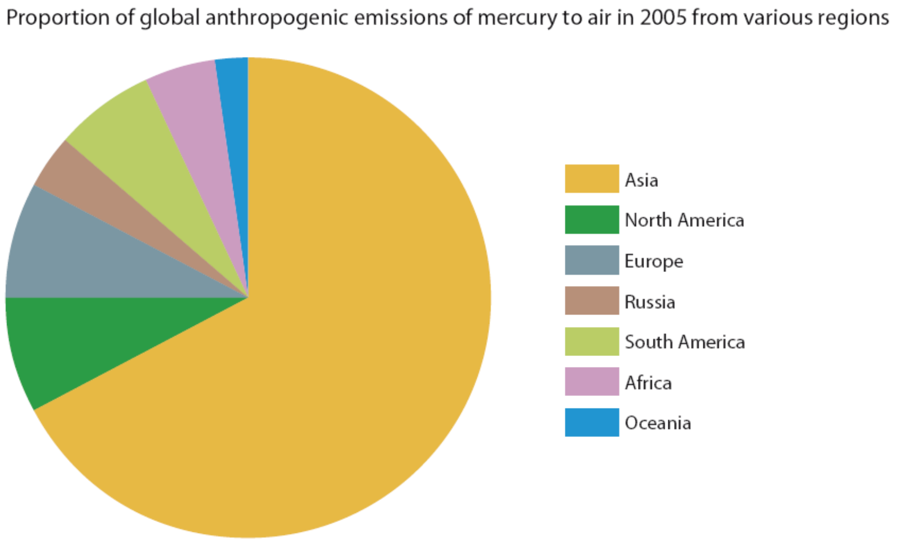

Figure 3: Global anthropogenic emissions of mercury to air in 2005 from different continents (UNEP, 2008).

Once released to the environment, Hg of anthropogenic origin is indistinguishable to naturally occurring Hg. In soils, water and vegetation Hg can be recycled back to the atmosphere and add to the global circulation. Important processes are evasion of elemental Hg from water surfaces and biomass burning. Biomass burning is not considered as a direct anthropogenic source because it is extremely difficult to distinguish between emissions from wild fires of natural origin and those from intentional burning and/or combustion of biofuel to produce energy. Nevertheless, biomass burning can be an important source of Hg emissions in certain regions and environmental recycling needs to be considered in the assessments of global transport and distribution of Hg.

2.2 Behaviour of mercury in the environment

The atmosphere represents the dominant fast pathway for the transport of Hg in the environment. Most Hg is emitted to the atmosphere in the form of gaseous elemental Hg (GEM), with minor amounts emitted as oxidized Hg either as oxidised Hg in the gas phase (also termed reactive gaseous Hg (RGM)) or as oxidised Hg associated with particles (total particulate Hg, TPM). GEM has a relatively long lifetime in the atmosphere (currently believed to be between 0.5 and 1.5 year), being slowly oxidized to either RGM or TPM, and thus Hg is found to be ubiquitous in the troposphere. RGM and TPM have much shorter lifetimes (hours to days) and are therefore subject to a relatively fast removal by wet or dry deposition. Schematic description of emission, chemical transformations and deposition of atmospheric Hg is shown in Figure 4.

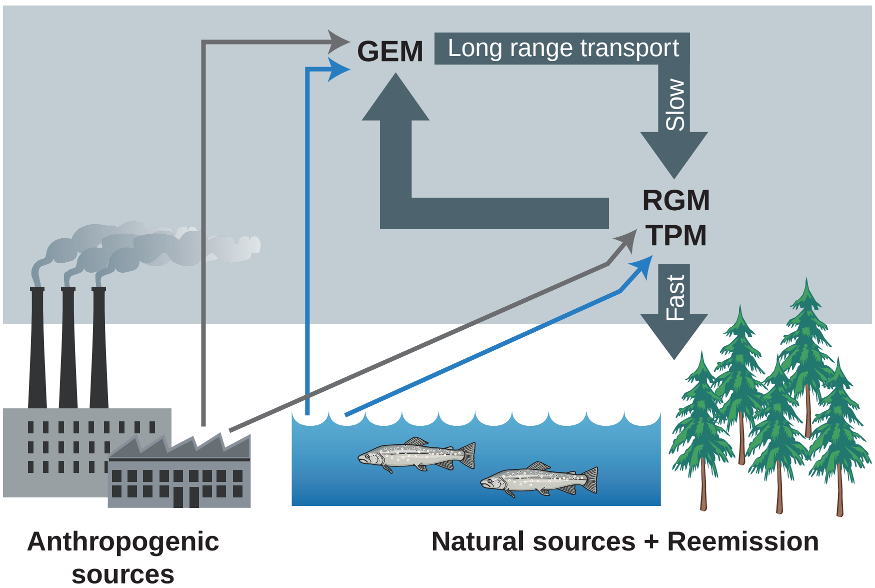

Figure 4: Schematic description of emission, chemical transformation and deposition of atmospheric mercury.

Deposited Hg can be converted back to volatile elemental Hg by chemical reactions (reduction reactions) in the soil or water or by bacteria, or alternatively converted by bacteria to methyl mercury (MeHg). Hg 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 Hg, even if originally emitted as RGM or TPM and deposited close to sources, can be transported towards colder regions. Recently, major review of our knowledge on atmospheric transport, chemical and physical transformations in the atmosphere and atmospheric deposition Hg has been carried out within UNEP (UNEP, 2008). It was concluded that chemistry is central for the understanding of the transport patterns of Hg, but there are large uncertainties in the description of the chemical removal of GEM from the atmosphere.

Atmospheric chemical transport models have been extensively applied during last decade to assess Hg levels in the ambient air and deposition fluxes both on global and regional scales. These models were also reviewed within the UNEP assessment (UNEP, 2008). It was concluded that contemporary models successfully reproduce elemental Hg concentration in the ambient air (uncertainty does not exceed 15-20%). Processes governing Hg 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 for estimates of dry deposition. Factors that are the most significantly affecting uncertainty of Hg deposition include emissions data (anthropogenic and natural), parameters of chemical reactions leading to oxidation of elemental Hg to short-lived forms as well as characteristics of dry deposition. An important factor restraining further improvement of Hg model is lack of regular measurement data, particularly, on air concentration of short-lived Hg species, dry and wet deposition.

Atmospheric models are also used to analyse source-receptor relationships. Relative importance of global versus regional sources and source-receptor relationships in the Northern Hemisphere were evaluated in Travnikov (2005). Particularly, it was obtained that about 40% of annual Hg deposition to Europe originates from external sources including 15% from Asia and 5% from North America. North America is more significantly subjected to influence of emission sources from other continents: up to 67% of total deposition to the continent originates from external anthropogenic and natural sources. Of this, about 24% can be apportioned to Asian sources and 14% to European. In contrast, the contribution of all external sources for Asia does not exceed 32%. Similar results for North America were obtained by Seigneur et al. (2004): North American anthropogenic emissions contribute 30% to total Hg deposition in the contiguous United States; other anthropogenic emissions contribute 37%, with Asia contributing the most (21%), whereas natural emissions account for 33%.

2.3 Environmental impacts of mercury

The UNEP assessment (UNEP, 2008) concluded that concentrations of Hg in ambient air are generally too low to represent any risk of adverse health effects for humans. The concern over Hg in the atmosphere is primarily related to its potential to be transported over long distances and the fact that, following deposition, it can be taken up by biota. Furthermore, Hg can bioaccumulate and biomagnify in the form of MeHg in food-webs, particularly aquatic food-webs, to levels that can be harmful to organisms, including humans. This can result in pollution problems in otherwise clean environments far from source areas, as has been documented in the Arctic (AMAP, 2002). The fact that Hg can be re-emitted (see below) means that the transport pattern is complex. Consequently, it is important to investigate the surface related chemistry of Hg by determining the fluxes of different Hg species over different surfaces. An illustration of major ecosystem inputs and outputs, as well as major aquatic pathways of Hg is presented in Figure 5.

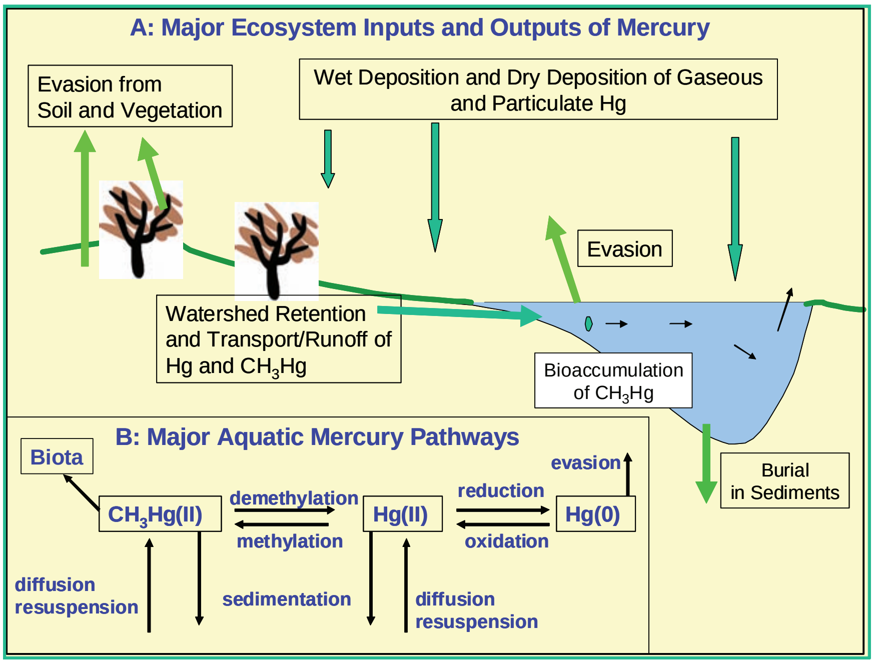

Figure 5: Major ecosystem inputs and outputs (A) and aquatic pathways of mercury (B).

Deposition increases of Hg above threefold have been documented near emission sources; depositions depend on stack height, the quantity and chemistry of the emitted Hg, and local atmospheric chemistry (Lindberg et al., 2007; Swain et al., 2007). Bacteria in aquatic systems convert a small proportion of the deposited Hg to MeHg, which bioaccumulates in fish (inorganic Hg does not bioaccumulate). Aquatic systems vary in the efficiency with which atmospherically deposited Hg is transformed to

MeHg and bioaccumulate in fish (Munthe et al., 2007). For example, the Hg concentration of fish in neighbouring lakes can vary by as much as 10-fold, even when atmospheric Hg levels are similar (Wiener et al., 2006)). Nevertheless, in a given aquatic system, the production of MeHg is believed to be approximately proportional to atmospheric Hg deposition (but with variable response time and magnitude), so it is likely that historical increases in Hg emissions have increased MeHg concentrations in fish (Munthe et al., 2007).

Major assessment of the environmental effects of Hg has been carried out within AMAP (2002). It was concluded that piscivorous fish and wildlife experience the greatest exposure to MeHg. The fish: pike, walleye, lake trout, bass, and pickerel, the birds: loons, kingfisher, bald eagles, herons and osprey, and the mammals: otter, mink, seal, polar bear, and certain whales were found as being particularly affected.

Concerning the effects, dietary MeHg could adversely affect reproduction in wild populations of fish in surface waters containing food webs with high concentrations of MeHg. Significant neuro-chemical effects have been documented in both wild mink and in captive mink fed with currently measured levels of MeHg. Impaired reproduction of birds was documented at currently measured levels of dietary MeHg intake. It is plausible that population level effects occur regionally, particularly in the most exposed cohorts of some piscivorous avian species.

2.4 Human health impacts

Consumption of fish is the major source of MeHg exposure to humans. For some populations, such as the indigenous groups in the Arctic, consumption of marine mammals such as whales is also a significant source of exposure to MeHg. Another source of exposure is consumption of animals that have been nourished with fish feed.

Various reference doses with regard to safe level of MeHg content in fish were proposed by various organizations, such as Food and Agriculture Organization (FAO), the European Commission, Health Canada, the U.S. Food and Drug Administration (FDA), the US EPA, ranging from 0.1 to 0.4 µg of MeHg per kg of body weight per day. It is very important that consumers are properly advised on the safe level of MeHg in fish.

Dietary MeHg is almost completely absorbed into the blood and distributed to all tissues including the brain; it also readily passes through the placenta to the fetus and fetal brain. Population groups who regularly and frequently consume large amounts of fish -- either marine species that typically have much higher levels of MeHg than other seafood, or freshwater fish that have been affected by Hg pollution - are more highly exposed. Because the developing fetus is the most sensitive to the effects from MeHg, women of childbearing age are regarded as the population group of greatest concern.

Concerning the impacts, MeHg is a developmental neurotoxicant at current environmental levels in many regions of the world. It can cause neurological effects, including reductions in IQ (Intelligence Quotient) among children. Among adults, neurobehavioral effects can be observed at moderately elevated exposures. There is also a body of evidence indicating elevated risk for cardiovascular diseases, especially myocardial infarction. In the situation of severe exposure, there is a risk for reproductive outcomes, immune system effects and premature death (Mergler et al, 2007 and Rae and Graham, 2004).

A database of health end points has recently been compiled within the EU DROPS project (http://drops.nilu.no) (Pacyna, J.M. 2008). Neurotoxic impacts were found to be the main human health end point for Hg. The most important studies on neurotoxic impacts due to Hg have followed cohorts of children among three populations in New Zealand, the Seychelles, and the Faroe Islands, whose diet contains a particularly large portion of seafood. Significant associations between exposure and neurotoxic impacts have been observed. For instance, 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 are then revised in Trasande et al. 2006. The revised function of DRF for Hg by Axelrad et al. (2007) is based on an integrative 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 impacts are relevant for children due to the transmission of toxic substance eaten by pregnant mother. Similar results are provided in the study of Billinger et al. (2006). Regarding the impacts among adults, no significant correlation with neurotoxic impacts was found due to the lower sensitiveness of the adult brain (Weil et al., 2005). There are other impacts due to Hg at low doses documented in the literature such as on coronary heart disease. However, except Rice and Hammitt (2005), the review by Virtanen et al. (2007) shows that the case seems to be less clear than for the neurotoxic impacts (quoted also in Spadaro and Rabl, 2008).

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

Quoting further Spadaro and Rabl, 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 point loss and 0.087 IQ points for zero threshold.

An important issue when discussing potential negative impacts of consumption of contaminated fish is that fish consumption *per se* is in general beneficial. Fish provides high nutritional value such as vitamins A, F, and C, protein, omega-3 fatty acids, mono-lipids, iron and zinc.

3. Costs of mercury pollution within the Status Quo scenario

The use of Hg, and the resulting emissions to air, water and soil have caused and are still causing negative impacts on society and the environment. These effects have a number of economic consequences. These consequences can be categorized into the following groups- damage costs; transactions costs; and abatement costs.

The damage costs are closely linked to negative effects on human health and the environment, in economic literature often named 'external costs', given that these costs are not considered internally in the economic decision process involving the use of Hg. Reduced commercial fisheries and reduced tourism due to contaminated fisheries can also be considered as damage costs in this context.

Transactions cost is a suitable term for summarising all the societal resources that are used because of the Hg problem. These resources include costs for; scientific research & Development to increase understanding of the Hg problem; administration costs, monitoring of Hg emissions and dispersion in the atmosphere; costs for legislation and enforcement of control measures; costs for risk communication and adaptation processes.

Abatement costs are directly linked to practical measures that either reduce the use of Hg or the emissions of Hg. These costs are often linked to investment in equipment as well as operational and maintenance costs.

For all these three main groups (damage, transaction, and abatement costs) there is a macro-economic element which involves opportunity costs (what other utility can be achieved with the resources spent on Hg control?) and the implied effect on economic growth.

Furthermore, the transaction costs are in the case of Hg not always directly linked to the actual emission levels. They are rather linked to the society's concern for negative impact of Hg pollution. This cost would therefore not change if emission changes.

3.1 Definition of Status Quo scenario

One of the goals of this project was to estimate the Hg emissions from anthropogenic sources in the year 2020 assuming that we continue to generate these emissions without additional legislation or control as in the year 2005. This 2020 emission scenario is called the Status Quo (SQ) scenario in the project. It was assumed that current practises and abatement techniques in controlling Hg emissions from various sources and uses of Hg that result in Hg emissions to air will continue until the year 2020. Economic growth is assumed to include those sectors that produce Hg emissions. However, emission control practices remain unchanged.

Emissions of Hg as a by-product in the year 2020 for the SQ scenario

Concerning the 2020 emissions from sources where Hg is a by-product, major focus was on the assessment of:

1. 2020 emission factors for individual source categories, and
2. Changes of production/consumption indexes between 2005 and 2020.

The emission abatement techniques and practises employed to reduce emissions of Hg in the year 2005 are described in detail in the UNEP Chemical project on qualitative assessment of the potential costs and benefits associated with emission reductions of Hg from various sources (Pacyna et al., 2008). In short, the application of electrostatic precipitators (ESPs), fabric filters (FFs) and to some extend flue gas desulphurization (FGD) installations is taken into account for major point sources of Hg emissions to the atmosphere, such as large electric and heat generating power plants, non-ferrous and ferrous smelters, cement kilns and waste incinerators. The efficiency of Hg removal for these emission control technologies, available from the database developed within the EU ESPREME project (http://espreme.ier.uni-stuttgart.de) was used to assess emission factors which were then used to estimate the emissions in the SQ scenario. These emission factors are also available in the ESPREME database for individual emission source categories. Thus, it is assumed in the SQ emission scenario that the 2005 emission factors will not change until the year 2020.

Economic activity is assumed to grow between 2005 and 2020, including those sectors that produce Hg emissions. The economic activities for the production of industrial goods, including energy, and the consumption of raw materials in the year 2020 were obtained from statistical yearbooks and models on energy and industrial goods production, such as the EU PRIMES model. This model is used to generate information needed within the CAFE´ (Clean Air for Europe) program (http://europa.eu.int/comm/environment/air/cafe/index.htm).

The 2020 SQ emissions estimated on the basis of emissions factors and statistical indexes mentioned above are presented in Table 1.

Table 1: Mercury by-product emissions from anthropogenic sources worldwide for the Status Quo scenario in 2020 (in tonnes).

Status Quo 2020	Source category								
Region	Stationary combus-tion	Cement produc-tion	Metals produc-tion	Large-scale gold production	Mercury production	Waste inciner-ation	Other	Total 2020	Total 2005
Africa	44	16	4.0	8.6	0.0	0.6		74	62
Asia (excl. Russia)	980	200	123	59.	8.8	2.1	0.6	1374	1026
Austra-lia/Oceania	19	0.6	6.9	10				37	37
Europe (excl. Russia)	77	28	19			10	15	148	145
North America	71	16	18	16	0.0	16	6.8	145	146
South America	11	9.5	15	16			1.5	55	50
Russia	52	5.8	7.8	4.3	0.0	3.5	1.5	75	70
Total	1253	278	194	114	8.8	33	25	1906	1535

Based on these figures it can be concluded that emissions of Hg from anthropogenic sources where Hg is a by-product will increase by the year 2020 by about one quarter in comparison to the 2005 level if we continue polluting the environment at the present level of ambition for Hg abatement.

Emissions from intentional use of mercury in the year 2020 for the SQ scenario

Concerning the 2020 emissions during various uses of Hg, very little data is currently available to support the development of future scenarios for Hg from product use, crematories and artisanal gold mining. Increased global supply and consumption of Hg may lead to increased emissions via several routes but if recycling and safe handling is implemented in more regions, emissions may decrease or stabilise. Another critical issue is management of household, medical and industrial waste. For emissions related to product use of Hg, the waste sector is responsible for the major part of the emissions. However, better waste management, recycling and controlled incineration or landfill disposal can reduce Hg emissions substantially. For artisanal gold mining the use of Hg is likely to continue or increase since it is driven by poverty. Even if Hg supply is decreased e.g. via restricting export and trade from Europe, illegal trade may replace this Hg and new or previously active Hg mines may be reopened.

For the SQ scenario, it has been assumed that the intentional use of Hg in the year 2005 will continue at the same level until the year 2020. Thus, the total consumption of Hg in the year 2020 is expected to be the same, based on contributions from various uses as presented in Figure 6.

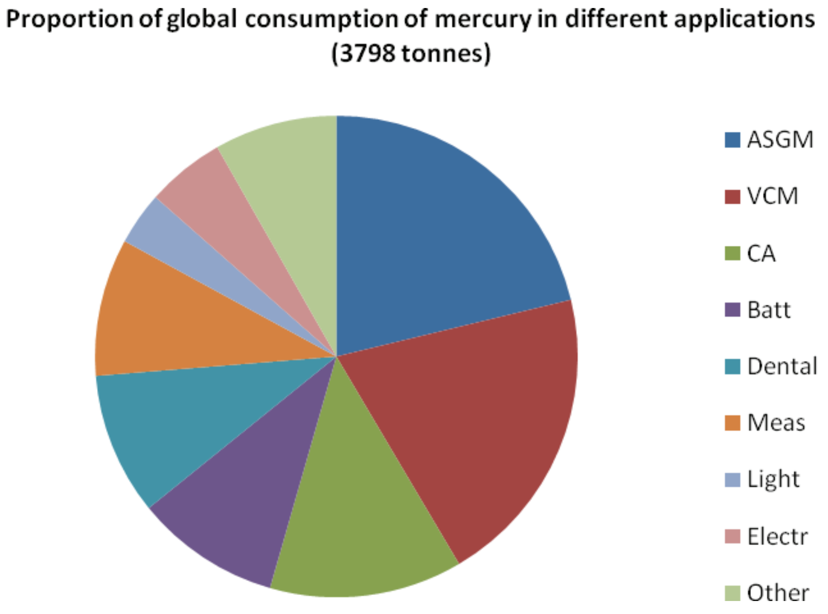

Figure 6: Global consumption of mercury in different applications for the Status Quo scenario in 2020 (3798 tonnes). For definition of consumption and categories see Abbreviations and Definitions

ASGM= Artisanal and Small-scale Gold Mining
VCM= Vinyl Chloride Monomer production
CA= Chlor-Alkali industry
Batt = Battery
Dental = Dental amalgam
Meas = Measuring and control devices
Light = Lamps
Electr = Electrical and electronic devices
Other = Other applications of mercury

The Hg consumption data for the year 2020 were then used together with the emission factors established for each application, separately to estimate emissions of Hg within the 2020 SQ scenario. These emission factors are presented in UNEP (2008). The Hg emissions for various Hg applications in the year 2020 within the SQ scenario are presented in Figure 7.

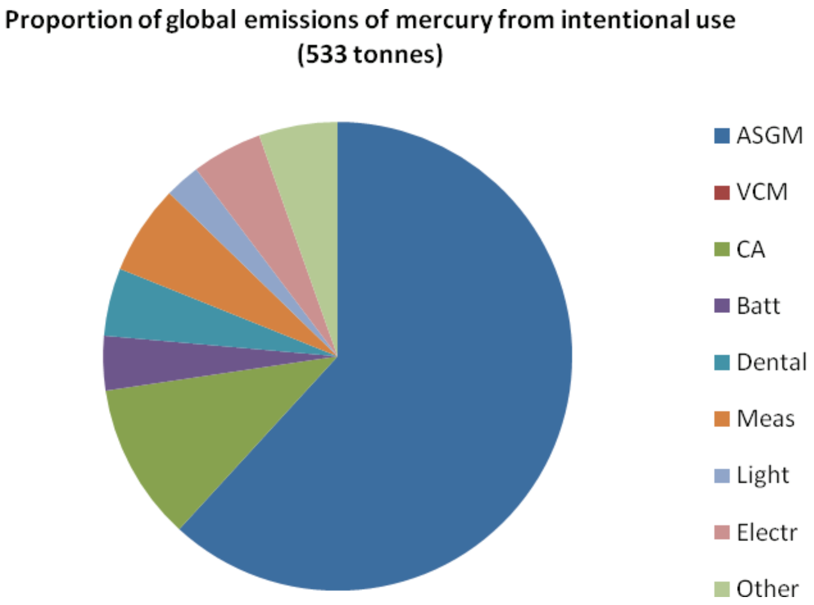

Figure 7: Global emissions of mercury from intentionally use for the 2020 Status Quo scenario (533 tonnes).

It should be noted that these estimates are limited to the emissions occurring during use and disposal of the product. Significant emissions may also occur during the production phase.

3.2 Damage costs of mercury pollution for the society

Information on the damage cost to society due to exposure to Hg pollution is needed for the assessment of total costs related to this pollution and to compare costs and benefits for different options of reduction of Hg pollution.

In this report, damage costs refer to the costs directly associated with measurable damages to human health. These damage costs are a subcategory to all the costs related to Hg pollution, as presented at the beginning of this chapter.

The damage costs are related directly to the dose of Hg received through inhalation of contaminated air and the ingestion of polluted food. This relation has been previously presented as the slope factor, linking IQ changes with intake of Hg containing food during pregnancy. The total damage cost related to welfare parameters of changes in development impairment have been reviewed in the DROPS project. This cost includes the cost related to loss of earnings, loss of education, as well as opportunity cost while at school (Scasny et al., 2008). Furthermore, the reduction in IQ might have a direct and indirect effect on earnings. The direct effect of reduced IQ is traced through its impact on job attainment and performance, i.e. lower IQs decrease job attainment and performance. Reduced IQ may also result in two indirect effects: reduced educational attainment, which, in turn, affects earnings and change in labour market participation.

A literature review related to damage cost based on IQ decrement (all studies conducted in the USA) was performed by Rabl and Spadaro (2006):

- Lutter (2000) indicates 3,000 € (US$ 4,500) per IQ point,
- Grosse et al (2002) estimate US$ 14,500 per IQ point,
- Muir and Zegarac (2001) estimate US$ 15,000 per IQ point,
- Rice and Hammitt (2005) indicate US$ 16,500 per IQ point, and
- Trasande et al (2005) indicate US$ 22,300 per IQ point.

Spadaro and Rabl (2008) concluded on the basis of their review that it is proper to use 10,000€ (US$ 15,000) per IQ point. The slope factor on IQ loss due to daily intake of MeHg used in their study was estimated to be 0.036 IQ points per µg/day. The methodology for estimating the global intake of MeHg and the damage cost, used in the DROPS project is presented in Appendix 1.

In the DROPS project, the total costs to society are given by the sum of the opportunity costs in terms of loss of labour productivity, direct costs of remedial education and the opportunity costs related to the remedial education. For the EU-27 countries, the total costs per IQ point was derived as high as 14,600 $€_{2005}$ (US$ 21,900) using a discount rate equal to 1% or about 6,300 $€_{2005}$ or US$ 9,450 (if the discount rate is 3%) assuming the effect of schooling by Salkever (1995) being 0.1007 years. If the effect on schooling as derived by Schwartz (1994) is assumed, the costs are 90% or 84% of the costs derived from the schooling effect estimated by Salkever using 1% and 3% discount rate, respectively.

Damage costs for by-product emissions of mercury in the SQ scenario

Estimates of damage costs due to ingestion and inhalation, in the year 2020 along the emission change assumptions within the SQ scenario are presented in Figure 8. These costs data are based on the cost estimates for the IQ loss in the DROPS project for inhalation of Hg polluted air and ingestion of Hg contaminated food, separately. In the DROPS project, a cost of 8,000 € (US$ 12,000) per 1 kg of Hg was used for the ingestion pathway. The methodology for estimating this damage cost due to ingestion of food contaminated by Hg is presented in Appendix 1 based on Spadaro and Rabl (2008) and used in the EU DROPS project (Scasny et al., 2008). These costs were used for assessments covering Europe. For global assessment, consideration must be taken of differences in economical situation in different countries. Valuation of IQ is country specific. Since making individual evaluations of IQ loss and associated costs for individual countries was not possible within the scope of this project, the values from some studied countries are transferred to others using Gross Domestic Product (GDP) per capita expressed as Purchasing Power Parity (PPP) as a weighting factor. The method is called benefit transfer using the formula:

$$c_i = c_{USA} \frac{(GDP_{ppp} / capita)_i}{(GDP_{ppp} / capita)_{USA}}$$

Where C_i is a damage cost in a specific country and C_{USA} is the damage cost in for example USA. Based on this formula the costs are dependant on the GDP_{ppp} per capita level in the studied country. Hence, a country with low GDP_{ppp} will have a lower IQ cost and vice versa for a country with a high GDP_{ppp}. .

In the case of inhalation, the amount of 0.8582 € (US$ 1.2873) per 1 kg of Hg (the case of Poland) was used for the countries in Asia (except Japan), Eastern Europe, Africa and South America, while 1.419 € (US$ 2.1285) per 1 kg of Hg was used for the rest of the world.

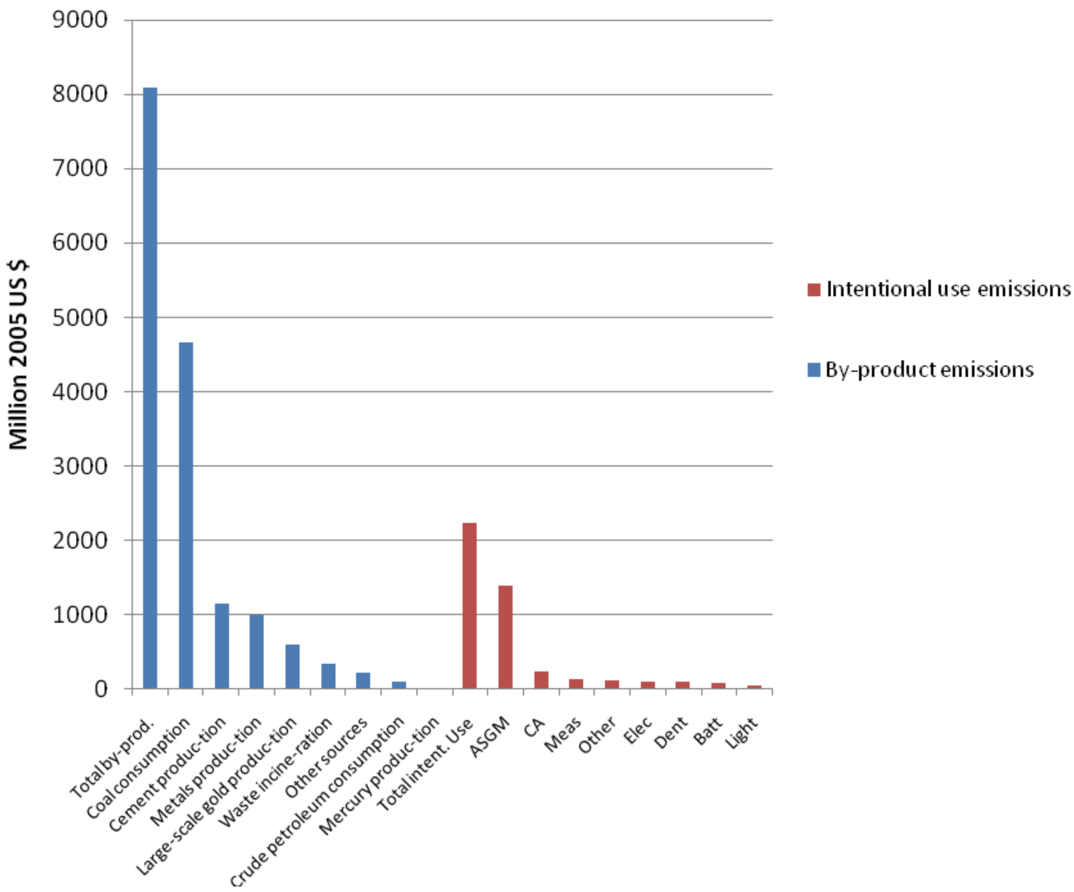

Figure 8: Annual damage costs due to ingestion and inhalation of Hg for by-product- and intentional use source categories in year 2020, SQ scenario, (million 2005 US$)

The damage costs due to ingestion and inhalation were estimated for various continents and source categories in year 2020 at the emission levels defined in the SQ. Without applying the GDP_{ppp} correction, the total damage costs are 23 billion US $ for by-product emissions and 6.4 billion US $ for emissions from intentional use. The corresponding global damage costs when applying the GDP_{ppp} correction are 8.1 billion 2005 US$ for by product emissions and 2.2 billion 2005 US$ from intentional use emissions. By far the highest damage cost of by-product emissions is associated with emissions from coal consumption and artisanal and small scale gold mining for emissions from intentional use. Herewith, only GDP-corrected damage cost data are presented and discussed.

The results which are presented in 2005 US$ are shown in Figure 8.

3.3 Additional estimates of damage costs

Other damage costs than IQ loss may also be important in an overall assessment. As presented in chapter 2.3 and 2.4 there are a number of other environmental and human health impacts that result in damage costs for society (also) discussed in the beginning of this chapter. The main environmental impacts concern impaired reproduction potential in wild populations of some species of fish and birds, as well as neuro-chemical effects on minks (and thus a potential risk for other fish-eating mammals). Apart from effects on IQ, human health impacts of concern from ingestion of MeHg are mainly related to neurological, cardiovascular, reproduction and the immune system.

Although their large potential importance, these adverse endpoints remain to be studied and quantified in a manner suitable for a comparison of costs and benefits. Exposure-response functions need to be established and the endpoints need to be valued. However, since no reliable estimates are currently available, the damage costs considered in this study are the damage costs related to IQ-losses.

A few studies attempting to estimate total human health benefits (i.e. including the above additional impacts) from reduction of Hg are available from site specific investigations. In a case study from 2004 (Rae and Graham, 2004) which comprises the South Atlantic coast from North Carolina to northern Florida in the USA, it is estimated that human health benefits (avoiding non-fatal heart attacks, all cause mortality and child hypertension) becomes about 7 times higher than if only the loss of IQ points was estimated. (It is important to note that the results may be influenced by the fact that the studied area is having 85 percent higher exposure levels than the USA in general). Adverse health effects were in this case valued by the cost of medical treatment to reverse the injury and work-loss days while the willingness-to-pay method was applied in valuing irreversible effects as premature death. The estimated results from

Rea and Graham (2004) are presented in Table 2. As can be seen in Table 2, mortality represents a large share of the costs.

Table 2: Estimated annual health endpoint benefits (millions 2003 US$) as presented in (Rae and Graham, 2004) Table ES-3, page ES-4. The scenarios 1, 2 and 3 represent a reduction in deposition of 12, 40 and 20 percent respectively to the studied area.

	Benefits of Avoiding Mercury Health Endpoints					
	IQ Points Saved	IQ<70	Non-fatal Heart Attacks	All Cause Mortality	Child Hyperten-sion	Total
Reduction scenario 1	$78.0	$0.5	$6.1	$534.6	$0	$619.2
Reduction scenario 2	$259.5	$1.6	$20.7	$1,820.0	$0.7	$2,102.5
Reduction scenario 3	$134.5	$0.8	$10.2	$890.9	$0.3	$1,036.7

For the valuation of environmental damage, very little information is available on impacts of Hg. A contingent valuation study conducted in eastern USA (Hagen et al., 1999), asked respondents about their willingness to pay for reducing Hg deposition in the Chesapeake Bay area. The estimated willingness to pay per household for reduction in deposition and the related standard errors are presented in Table 3 where the willingness to pay to reduce depositions by 21% is 160 US$. N depicts the number of households included in the study.

Table 3: Estimated willingness to pay for mercury reduction in deposition as presented in (Hagen et al., 1999), Table IX-3.

Subsample (listed by % reduction in deposition)	Estimated WTP (US$)	Standard Error	N
5%	120.96	52.19	159
12%	118.91	24.84	348
21%	160.22	81.05	164
35%	225.57	173.72	174

4. Evaluation of regions that will face the highest impacts of continued mercury pollution

4.1 Identified regions of high impacts

Due to its capacity for global transport, mercury contamination can occur in all regions of the world. Large impacts are expected in highly contaminated areas in the vicinity of sources as is the case for many environmental contaminants. These are of great importance when assessing the overall impacts of mercury contamination and the benefits of reducing emissions, but these assessments can only be made with information about local conditions and extent of contamination. For remote areas, a wealth of scientific literature is available describing mercury inputs and cycling as well as exposure and impacts in e.g. the Nordic Countries, North America and the Arctic. In the 2002 UNEP Global Mercury Assessment (UNEP, 2002), information on environmental levels and human exposure to mercury via fish consumption and other pathways was compiled. For many regions, information is very scarce and a global assessment of the actual impacts is difficult to make based on available measurement data. Nevertheless, it was concluded that a significant portion of humans and wildlife throughout the world are exposed to methyl mercury at levels of concern, primarily due to consumption of contaminated fish.

In the absence of data on fish contamination, consumption patterns or exposure levels, it is difficult to identify in detail which population groups in which regions are most severely affected and bear the cost of mercury contamination. Nevertheless, by examining the geographical distribution of emission and deposition of mercury along with global statistics on fisheries and fish consumption, a rough assessment of risk can be made to identify regions of specific concern.

4.2 Geographical distribution of emissions and deposition of mercury

The largest emissions of Hg at present and in the near future are estimated for the Asian countries. The emissions estimates for the year 2005 are presented in Figure 9. China, with its more than 2000 coal-fired power plants, and other large industrial activities is the largest single emitter of Hg worldwide. Equally significant are emissions from combustion of poor quality coal mixed with various kinds of wastes in small residential units to produce heat and cook food in rural areas.

Together, three countries, China, the USA and India, are responsible for about 55% of the total global Hg emissions from by-product sectors (i.e. 1535 tonnes). More information on this subject is available from the UNEP assessment of global emissions of Hg (UNEP, 2008)).

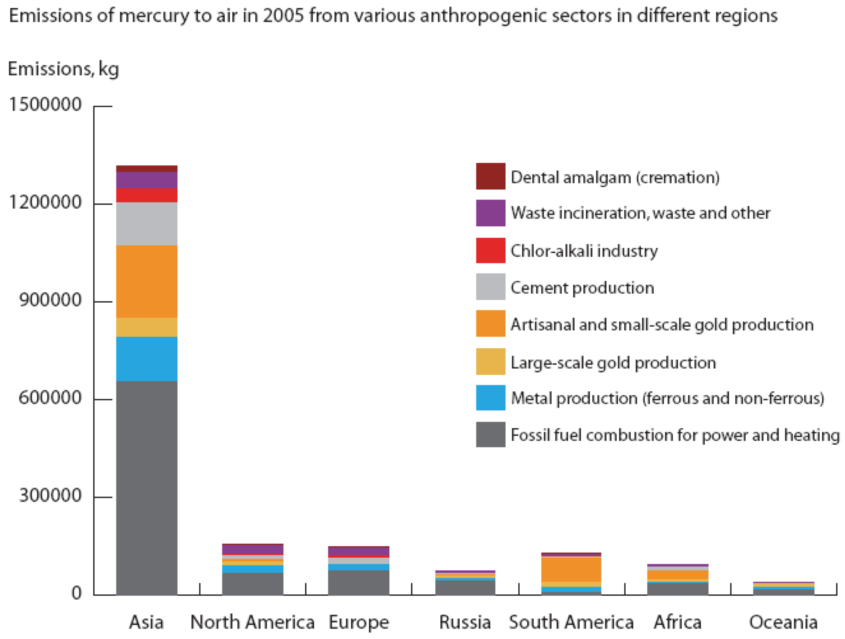

Figure 9: Global anthropogenic emissions of mercury to air from different continents by sector in 2005.

The spatial distribution of Hg emissions from by-product sources and Hg uses in 2005 is presented in Figure 10.

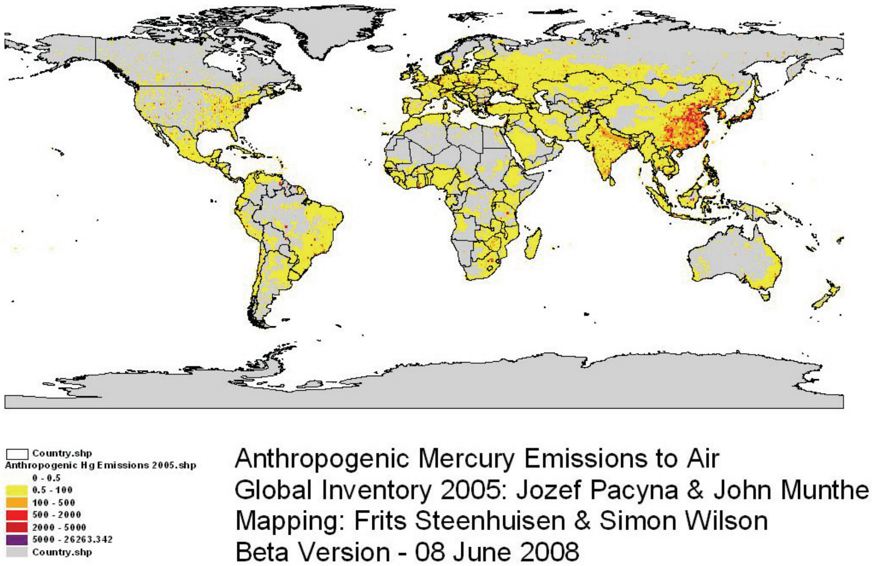

Figure 10: Spatial distribution of Hg emissions from anthropogenic sources worldwide within 1° by 1°

The emissions maps, such as the 2005 emission map in Figure 10 mimic quite closely the maps of atmospheric deposition of Hg, reviewed recently within the UNEP GLOMER project (UNEP, 2008). An example of such deposition map is presented in Figure 11.

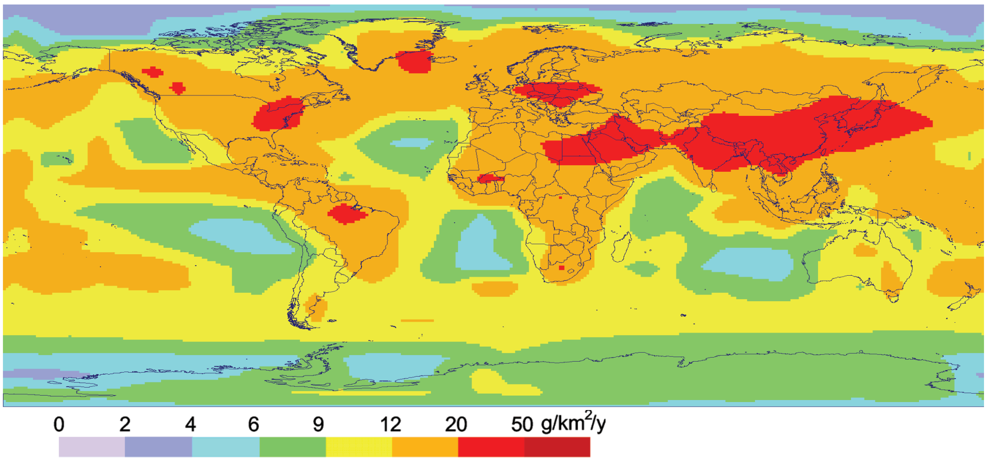

Figure 11: Global distribution of total (wet and dry) deposition of mercury in 2001 simulated by CTM-Hg model as cited in UNEP, 2008

The emission and deposition maps indicate that the most damaged regions due to Hg pollution in the year 2020 would be located in the south and south-east Asia, east and west Africa, and east and west South America. While these regions in Asia would be affected by pollution from a combination of coal-fired power plants and artisanal gold mining, the latter source contributes significantly to the environmental impact in Africa and South America.

A coarse map of ASGM Hg use is presented in Figure 12. This picture serves as a coarse indicator of where environmental and health impacts related to ASGM may be observed or can be expected. For population groups associated with ASGM, inhalation of Hg vapour is most likely the most significant exposure pathway.

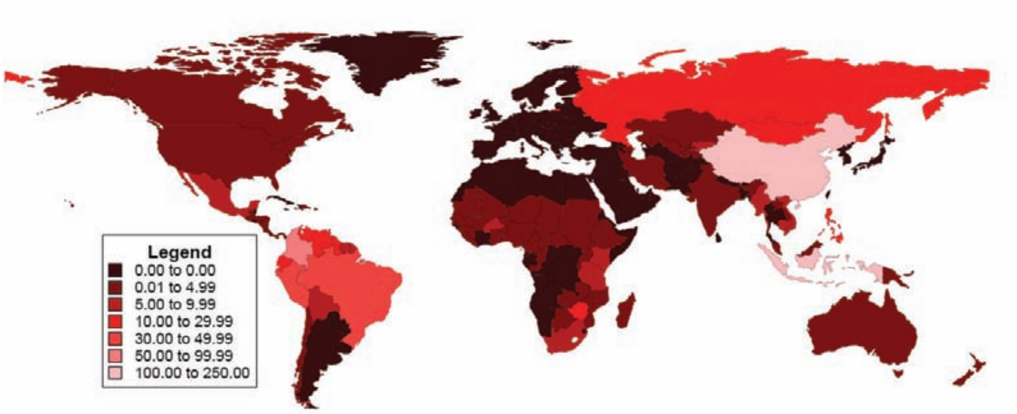

Figure 12: ASGM Mercury Consumption in the World regions [tonnes]. Source: Telmer, April 2008, presentation in Rome

4.3 Fish consumption as an indicator of potential risk

As has been presented in chapter 1.4, the consumption of fish is generally the most potent pathway for health effects caused by Hg. Concentrations of MeHg in fish varies greatly between fish species as well as between geographical locations. Nevertheless, current and expected fish consumption in various parts of the world can serve as a rough indicator of where potential risks of human health impacts from Hg exposure may be expected.

In Table 4 an overview of the global fisheries over the period 2001 - 2004 is presented.

Table 4: Production and utilization of fisheries and aquaculture (million tonnes)

PRODUCTION	2000	2001	2002	2003	2004
INLAND					
Capture	8.8	8.9	8.8	9	9.2
Aquaculture	21.2	22.5	23.9	25.4	27.2
Total inland	30	31.4	32.7	34.4	36.4
MARINE					
Capture	86.8	84.2	84.5	81.5	85.8
Aquaculture	14.3	15.4	16.5	17.3	18.3
Total marine	101.1	99.6	101	98.8	104.1
TOTAL CAPTURE	95.6	93.1	93.3	90.5	95
TOTAL AQUACULTURE	35.5	37.9	40.4	42.7	45.5
TOTAL WORLD FISHERIES	131.1	131	133.7	133.2	140.5
UTILIZATION					
Human consumption	96.9	99.7	100.2	102.7	105.6
Non-food uses	34.2	31.3	33.5	30.5	34.8
Population (billions)	6.1	6.1	6.2	6.3	6.4
Per capita food fish supply (kg)	16	16.2	16.1	16.3	16.6

Source: FAO 2007

In 2004, 106 million tonnes of fish, molluscs and crustaceans was consumed as food globally. 45 million of these were produced in aquaculture cultivation sites, out of which 27 were produced from inland waters.

Globally, 16.6 kg/capita of fish was consumed in year 2004. Of these, approximately 7 kg originated from aquaculture. The global share of fish products from aquaculture has increased constantly since the 70-ies. Figure 13 shows the fishery food consumption per capita for the period 1970 to 2004. Indicated in dark blue is the consumption of fishery food from aquaculture, indicated in light blue is consumption from fisheries.

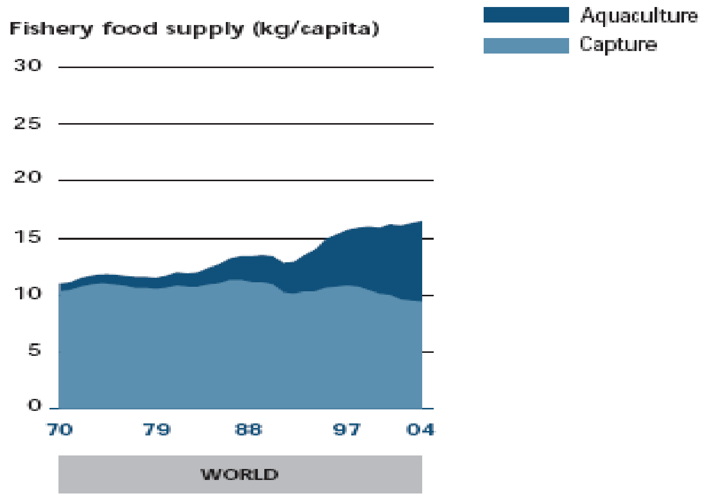

Figure 13: Global consumption of food fish from fisheries capture and aquaculture (Kg/capita 1970-2004). Source: FAO 2007

In an effort to derive regional information on fish consumption on a per capita basis, an indicator is derived from available FAO statistics (FAO 2007).

The following per capita estimates serves merely as an indicator of risk for Hg exposure via ingestion. The indicator is derived using the assumptions that:

- National production from fisheries and aquaculture reflects the national food fish consumption (no data on fish consumption with global coverage was available),
- Consumption of fish from aquaculture does not lead to significant Hg exposure (assumes low levels of Hg in fish fodder and limited bioaccumulation),
- The distribution between food and other uses is identical for all countries,
- The indicator of risk of Hg via ingestion is related to food consumption of fish

In order to derive an indicator, the FAO national data on aquaculture is subtracted from the national data on fish production. Furthermore the amount of fish produced for other purposes than food is also subtracted from the FAO data on fish production. The result is then divided by the population size in each country. The unit of the indicator is in "non-aquaculture food fish production / capita" and does not take into account trade of captures or origin of fish capture.

Table 5 show the results over regions and gives a potential indicator of risk estimate of Hg exposure from ingestion. For each region, the median value from available data is used as an indicator of fish consumption per capita, with outliers identified.

Table 5: Potential indicator of risk for mercury exposure via ingestion (Kg/capita)

	Average	Median	Low	High
Africa	3.8	2.7	0.0	502.3
Asia (excl. Russia)	9.8	2.8	0.0	27.4
Australia/Oceania	18.0	19.7	5.7	199.8
Europe (excl Russia)	9.1	2.3	0.1	2527.5
North America	7.6	4.5	0.4	31.5
South America	21.6	11.7	0.4	151.5
Russia	9.1	9.1	9.1	9.1

Data source: FAO 2007 (own calculations)

Table 5 shows for instance that Australia / Oceania and South America can be at risk for high Hg exposure based on the fact that average fish consumption is high i.e. 18 kg/capita. The production for export is also visible in the high estimates (Iceland for example produces 2527 kg fish products per capita during 2004). These numbers should not be directly compared to the global estimate of 16.6 kg / capita consumed in 2004, but serves only as a comparison between the studied regions.

When combining the estimates from table 5 above and the deposition estimates shown in Figure 11 above, the indicator estimate indicating Australia/Oceania and South America as sensitive areas remains. This indicator of risk estimate is dependent on the assumption that fish is captured recently close to the region. What is excluded from the Table 5 above due to the level of aggregation chosen is the situation in South-East Asia. In this region, the growth of aquaculture is strong, but at the same time the use of inland fish is very large, and the food fish consumption per capita is growing. Combined with the very large Hg deposition over South-East Asia, the overall indication is that South-East Asia is experiencing a fairly strong risk for high exposure to Hg via ingestion.

FAO (2007) has made prognoses on fish production and use in the future, summarised in Table 6. The overall picture is that fish food consumption will continue to increase. However, large uncertainties relate to the growth of aquaculture and other uses than food consumption (animal fodder).

Overall, the scenarios for 2020 indicate that world consumption of food fish will reach ~130–140 million tonnes, and aquaculture will supply ~50–70 of these. Of importance for future estimates on Hg exposure is how aquaculture will continue to evolve. A fast development of the aquaculture industry will reduce the risk of Hg exposure due to food fish consumption. Estimate on whether the risk for Hg exposure will increase or decrease is totally dependent on this parameter. Furthermore, the indicator of risk estimate related to fish consumption will vary with what future levels of Hg emissions that are expected. If Hg emissions and depositions are low, the risk induced by high fish consumption will be low. Correspondingly, high emissions and depositions will enhance the strength of fish consumption as an indicator of risk.

Table 6: Statistics and prognosis for global fish production and consumption (million tonnes)

			Simulation	target	year		
million tonnes	**2000**	**2004**	**2010**	**2015**	**2020**	**2020**	**2030**
Marine capture	86.8	85.8	86		87	–	87
Inland capture	8.8	9.2	6		6	–	6
Total capture	95.6	95	93	105	93	116	93
Aquaculture	35.5	45.5	53	74	70	54	83
Total production	131.1	140.5	146	179	163	170	176
Food fish production	96.9	105.6	120		138	130	150
Percentage used for food fish	74%	75%	82%		85%	77%	85%
Non-food use	34.2	34.8	26		26	40	26
Information Source	FAO Statistics	FAO Statistics	SOFIA 2002	FAO Study	SOFIA 2002	IFPRI Study	SOFIA 2002

To summarise, fish consumption is a rough but important indicator of risk for Hg-induced health effects. A more accurate analysis of potential risks from fish consumption would require detailed information on fish species consumption patterns as well as MeHg levels in the consumed fish.

It should be noted that the estimates presented here are only relevant for potential exposure related to fish contaminated by long-range atmospheric transport of mercury. Use and releases of mercury to water from e.g. artisanal gold mining, uncontrolled waste handling or product use may lead to significant exposure and impacts on the local scale and thus a different classification of regions at risk.

5. Some socio-economic costs and benefits of reducing mercury pollution beyond the Status Quo scenario

5.1 Abatement measures

There exist technological and non-technological measures that can efficiently reduce emissions of Hg to the atmosphere by the year 2020. Therefore, emissions estimated for the 2020 SQ scenario can be lowered even below the 2005 emission level by applying these measures. The emissions for these scenarios are presented in Figure 14. There are also emerging measures that will be available in the year 2020 to reduce the emission level estimated in the SQ emission scenario.

The type and efficiency of technological and non-technological measures to reduce emissions of Hg from different sources are reviewed in the UNEP-CBA project (Pacyna et al., 2008). The abatement costs and environmental benefits are also reviewed in this assessment. It has been concluded that a number of technical and non-technical measures are available for reducing the Hg emissions from:

- anthropogenic sources where Hg is a by-product (e.g. power plants, smelters, cement kilns, other industrial plants),
- intentional uses, and
- waste disposal.

However, these measures differ with regard to emission control efficiency, costs, and environmental benefits obtained through their implementation. Very often Hg emissions are substantially reduced by equipment employed to reduce emissions of other pollutants. The best example is the reduction of Hg emissions by the flue gas desulphurization (FGD) installations. Removal efficiency of FGD installations for Hg ranges from 30 to 50%. The same applies to de-NOx installations, and control devices reducing emissions of fine particles. Hence, it can be concluded that the technical measures for Hg emission reduction in some regions are in place within the major emission sources categories, such as combustion of coal to produce electricity and heat, manufacturing of non-ferrous metals, iron and steel production, cement industry and waste incineration.

Higher Hg emission control efficiencies, exceeding 95 %, can be obtained through a combination of FGD and electrostatic precipitators (ESPs) or fabric filters (FFs) with “add on” type of equipment, specific for removal of Hg from the flue gases, including carbon filter beds and activated carbon injection. However, the combined solutions are very expensive and they are used only at a few sites around the globe.

The UNEP CBA study (Pacyna et al., 2008) also concludes that efficient, non-technological measures and pre-treatment methods are also available for the reduction of Hg releases from various uses of products containing Hg. These measures include ban on use and substitution of products containing Hg, and 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 Hg emissions also comprise prevention options, aimed at reducing Hg in wastes and material separation, labelling of Hg containing products, and input taxes on the use of Hg in products.

The message from the review of abatement installations for reduction of Hg emissions from various anthropogenic sources from the UNEP CBA project is that there are a number of technological and non-technological solutions available which could be employed at present in order to reduce Hg emissions in the year 2020. Of course, it is expected that even more technological measures will be available in the near future, particularly in the field of application of renewable sources of energy production and the improvement of Hg removal using the “add on” measures in addition to ESPs/FFs combined with FGDs. There is also a great potential for improvement of non-technological measures such as decrease in the use of Hg in the future, and development of incentives for application of measures aiming at reduction of Hg emissions to the environment.

5.2 Emission reduction scenarios for the year 2020

In order to estimate the potential benefits of reducing the damage costs caused by Hg emissions, additional scenarios for future emissions have been analysed. Detailed presentations of these scenarios can be found in UNEP (2008), These emission scenarios are based on the application of technological and non-technical measures to reduce emissions and indicate that atmospheric emissions of Hg in the year 2020 can be reduced significantly not only from the levels expected in the Status Quo (SQ) scenario but also in relation to the 2005 emission levels.

Emission reduction scenarios for by-product sources

The development of two scenarios projecting the application of technological and non-technological measures of Hg emission reductions, namely the EXEC (Extended Emission Control) and MFTR (Maximum Feasible Technical Reduction) scenarios, has been done within the UNEP-GLOMER project (UNEP, 2008) , see Appendix 2 for details.

The Hg emissions in the year 2020 along the assumptions defined within the EXEC and MFTR scenarios are estimated to be 966 tonnes and 751 tonnes, respectively. Details on methodology of emission estimates are presented in the UNEP GLOMER project report (UNEP, 2008).

A comparison of Hg emissions from by-product sources in the year 2005 with the 2020 SQ, EXEC and MFTR emission scenarios for various regions in the world is presented in Figure 14.

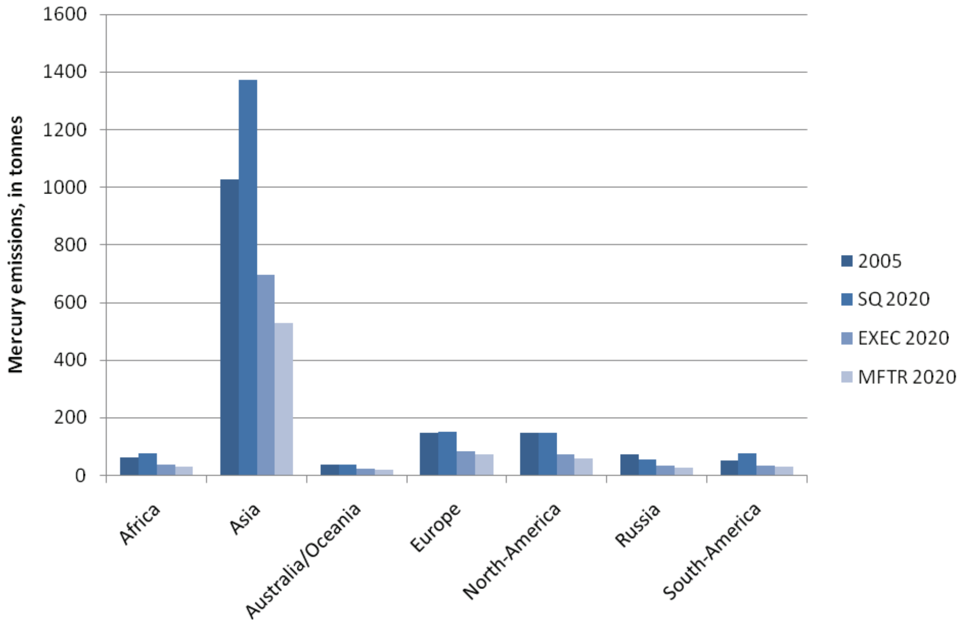

Figure 14: Comparison of emissions of mercury as a by product in the year 2005 with the 2020 emission scenarios for various regions worldwide.

The largest increase of Hg emissions from by-product sources in the period from 2005 until 2020 is expected in Asia assuming that the current Hg pollution will continue until 2020 (the SQ scenario). Detailed analysis carried out within the UNEP GLOMER project (UNEP, 2008) indicate that the increase of Asian emissions is primarily due to expected increase of Hg emissions in China followed by India.

Clear decrease of Hg emissions from by-product sources between 2005 and 2020 are seen for all continents for the emission scenarios EXEC and MFTR assuming implementation of efficient emission control devices. As expected, the largest emissions of Hg in 2020 are estimated for Asia.

The decreases of Hg emissions in Europe, the North America, Australia, Japan and Russia are expected to be between 40 and 60 %.

A comparison of the 2020 global emission data estimated for the EXEC and MFTR scenarios with emissions of the 2020 SQ scenario and the 2005 emission data for various source categories is shown in Figure 15.

It can be concluded that a decrease by one third of the total emissions of Hg in 2005 can be expected in 2020 if the assumptions of the EXEC are met. As much as a half of the 2005 total emission can be reduced by 2020 if the assumptions of the MFTR scenario are met. These decreases of total emissions of Hg between 2005 and 2020 are clearly driven by the decreases in Hg emissions in this period calculated for the consumption of coal to produce electricity and heat. However, there is also a clear decrease in Hg emissions estimated for various industrial sectors, such as cement production and ferrous and non-ferrous metal production.

A comparison of the 2020 emission data estimated for the EXEC and MFTR scenarios with emissions of the 2020 SQ scenario and the 2005 emission data for various source categories is shown in Figure 15.

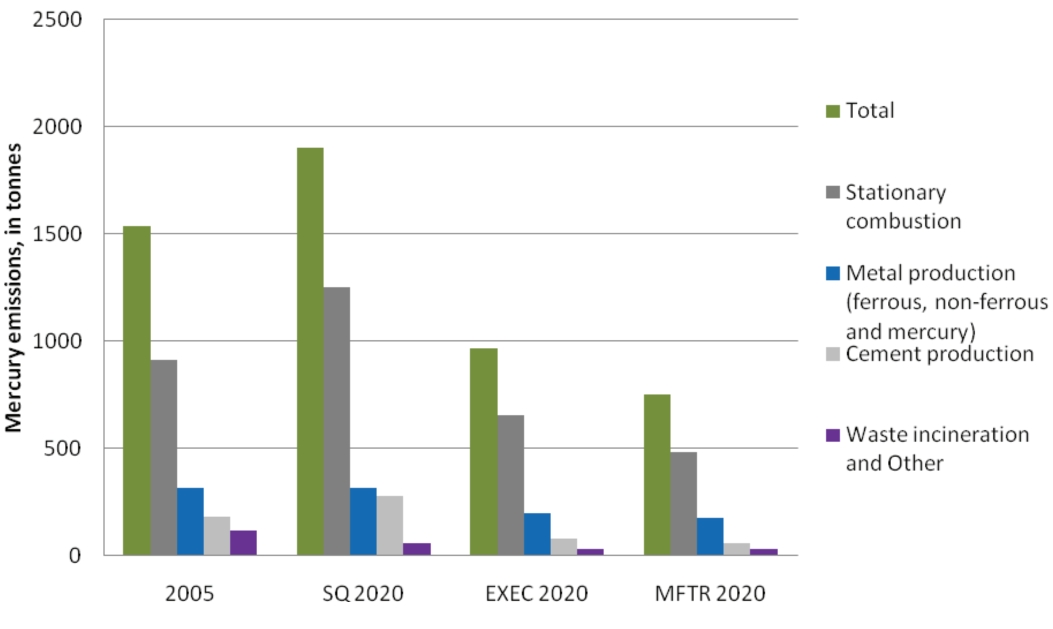

Figure 15: A comparison of the 2020 emission data estimated for the EXEC and MFTR scenarios with emissions of the 2020 SQ scenario and the 2005 emission data for various source categories

A comparison of the 2020 emissions within the EXEC scenario and the SQ scenario indicates that as much as 939 tonnes of Hg could be emitted worldwide in 2020 in addition to the projected 966 tonnes (the EXEC scenario), if pollution of the environment by Hg will continue along present conditions. In other words, the implementation of basic assumptions on reduction of Hg emissions until the 2020, defined within the EXEC scenario will result in a benefit of reducing 939 tonnes of this pollutant. This means, that doing nothing for the improvement of the Hg emission reductions will cause an increase of the emissions in 2020 by almost 100 % compared to the EXEC scenario. Even larger increase is estimated when the 2020 SQ scenario of Hg emissions is compared with the 2020 MFTR emission reduction scenario. Emissions of Hg in various industrial sectors, such as cement production and metal manufacturing in the year 2020 can be 2 to 3 times larger if nothing will be done to improve emission control in comparison with the EXEC scenario.

In summary, significant reductions of the 2005 Hg emissions can be obtained in the year 2020 if the available and emerging measures, both technological and non-technological are implemented.

Emission reduction scenarios for intentional use of mercury

Scenarios for future intentional use of Hg are uncertain due to the lack of consistent international agreements or policies to reduce Hg demand. In many countries and regions, large efforts are nevertheless being made to reduce Hg 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. In UNEP (2006), two future scenarios for Hg consumption in different categories were defined. The scenarios were based on a partly qualitative discussion of reduction potentials and on-going activities to reduce demand. To take into account the unavoidable uncertainties, two different scenarios were prepared: "Status quo scenario" and "Focused Hg reduction scenario". In this report, the "Focused Hg reduction scenario" will be used as a part of the EXEC (Extended Emission Control) scenario. For Status Quo scenario, the data on use and emissions presented in UNEP (2008) are used, as explained earlier. In addition to this, a Maximum Feasible Technical Reduction (MFTR) scenario has been

Table 7: Consumption of mercury in different applications with the 2020 SQ, EXEC, and MFTR scenarios

	SQ 2020	EXEC 2020	MFTR 2020
ASGM	806	400	400
VCM	770	1000	500
CA	492	250	0
Batt	370	100	50
Dental	362	230	165
Meas	350	100	50
Light	135	100	50
Electr	200	90	45
Other	313	30	15
Sum	3798	2300	1275

developed. This scenario is based on an overall assumption of 50% reduction of Hg used in comparison to the EXEC scenario with the additional assumption of a 75% reduction in the Chlor-Alkali (CA) industry.

For Artisanal and Small-scale Gold Mining (ASGM), no change in consumption is assumed in comparison to the EXEC scenario. This is motivated by the expected difficulties in managing this largely unregulated sector. In Table 7 the consumption of Hg in these scenarios is presented for different applications.

In UNEP (2008), emissions to air of Hg from the various use categories were estimated based on a simple material flow analysis. For estimating emissions in the 2020 SQ, EXEC and MFTR scenarios, the emissions were scaled down according to the reduction in consumption. It should be noted that no estimates were presented for the Vinyl Chloride Monomer (VCM) sector due to a lack of information. Estimated emissions from the various scenarios and sectors are presented in Table 8.

Table 8: Emissions of mercury 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.
CA	58	29	0
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	533	247	195

N.A. = not available

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

5.3 Damage costs related to Hg emissions to the atmosphere

Damage costs from by-product sources

Damage costs due to ingestion and inhalation in the year 2020 along the emission reduction assumptions defined within the EXEC and MFTR scenarios was calculated assuming a discount rate of 4%. The results are presented in Table 9. The estimates for the SQ scenario are also included for comparison purposes.

Table 9: Annual damage costs in the year 2020 due to IQ loss following ingestion and inhalation of mercury along the emission reduction assumptions within the SQ, EXEC, and MFTR scenarios for by-product sources (2005 US$).

	SQ 2020			EXEC 2020			MFTR 2020		
Category	Ingest.	Inhal.	Total	Ingest.	Inhal.	Total	Ingest.	Inhal.	Total
	mill. US$	Thous. US$	mill. US$	mill. US $	thous. US$	mill. US$	mill. US$	thous. US$	mill. US$
Coal consumption	4664	1798	4665	2187	923	2188	2057	688	2058
Crude petroleum consumption	104	25	104	46	13	46	34	10	34
Cement production	1150	562	1151	337	117	338	246	85	246
Metals production	994	283	994	386	115	386	282	84	282
Gold production	598	162	598	598	162	598	598	162	598
Mercury production	16	11	16	16	11	16	16	11	16
Waste incineration	351	64	351	74	14	74	54	10	54
Other sources	220	50	220	220	50	220	220	50	220
Total	8082	2955	8085	3863	1404	3865	3075	1100	3077

The results presented in Table 9 conclude that the damage cost of Hg pollution due to ingestion of Hg contaminated food (presented in Table 9 in *million* 2005 US$) is significantly higher that the damage cost of Hg pollution due to inhalation of Hg polluted air (presented in Table 9 in *thousand* 2005 US$). The difference between these costs is so large that the damage cost due to Hg pollution by inhalation can be omitted in the analysis of total societal damage costs due to Hg pollution.

Damage costs related to the Hg emission from intentional mercury uses

Damage costs due to ingestion in the year 2020 along the emission reduction assumptions within EXEC and MFTR scenarios for intentional Hg use are presented in Table 10. The damage cost for SQ scenario is also included for comparison.

Table 10 indicates the damage costs caused by Hg emissions from intentional use. The benefits from reduced Hg exposure are given by the difference in societal damage costs between the different scenarios. The changes in damage costs are largest for ASGM and CA, where the total decreases in Hg use are the largest. The difference between EXEC and MTFR are not that large, mainly since the ASGM emissions are identical for the two scenarios.

Table 10: Annual damage costs due to ingestion in the year 2020 for the emission scenarios SQ, EXEC and MFTR for intentional mercury use (Million 2005 US$)

Category	SQ 2020	EXEC 2020	MFTR 2020
ASGM	**1386**	**669**	**649**
VCM	**N.A**	**N.A**	**N.A**
CA	**244**	**118**	**0**
Batt	**84**	**20**	**12**
Dent	**105**	**65**	**44**
Meas	**139**	**37**	**20**
Light	**55**	**37**	**20**
Elec	**109**	**45**	**24**
Other	**122**	**12**	**4**
Total	**2239**	**1008**	**772**

5.4 Societal benefits of mercury reduction until 2020

Societal benefits due the Hg emission reduction from by-product sources

The societal benefits in the reported project were estimated as the difference between the damage costs estimated for the SQ scenario on the one side and the EXEC and MFTR scenarios on the other one. In this way the societal benefits in monetary forms resulting from the employment of abatement equipment needed to obtain the targets of emission reductions defined in the EXEC and MFTR scenarios, are separately estimated. The results of these estimates for various regions are presented in Table 11.

Table 11: Societal annual damage costs and benefits related to ingestion of fish contaminated by atmospheric emissions and long-range transport of mercury estimated for various regions in the world due to implementation of emission reduction measures according to the 2020 EXEC and MFTR scenarios (million 2005 US$)

Region	Societal damage costs			Societal benefits	
	Status-quo	EXEC	MFTR	EXEC	MFTR
Africa	526	282	242	244	284
Asia (excl. Russia)	3402	1631	1220	1771	2182
Australia/Oceania	406	219	184	187	222
Europe (excl. Russia)	1073	541	454	532	619
North America	2138	939	767	1199	1371
South America	176	100	88	76	88
Russia	361	153	119	242	242
Total	8082	3865	3077	4217	5005

The comparison of the costs in Table 11 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 will result in lowering the societal (damage to society) costs by more than a factor of

2. This 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 Hg are expected. See discussion in Section 5.6.

Societal benefits due to Hg emission reduction from intentional mercury uses

For the intentional uses of Hg 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 fact that the regional link between end-use of a product and following emission is difficult to estimate. Table 12 shows the distribution of societal benefits for the two different abatement strategies.

Table 12: Societal damage costs and benefits related to ingestion of fish contaminated by atmospheric emissions and long-range transport of mercury from intentional use categories according to SQ, EXEC and MFTR scenarios 2020 (in 2005 million US$).

	Societal Damage Cost			Societal benefit	
Category	**SQ 2020**	**EXEC 2020**	**MFTR 2020**	**EXEC 2020**	**MFTR 2020**
ASGM	1386	669	649	717	737
VCM	N.A	N.A	N.A	N.A	N.A
CA	244	118	0	126	244
Batt	84	20	12	64	72
Dent	105	65	44	40	61
Meas	139	37	20	102	119
Light	55	37	20	18	35
Elec	109	45	24	64	95
Other	122	12	4	110	118
Total	2239	1008	772	1231	1467

Similar to the situation for the unintentional uses, the EXEC scenario reduces the societal damage costs by more than half, thereby inducing societal benefits of more than 5 billion US$ in total. By implementing the MFTR scenario, additional benefits of 1 billion US$ would be reached in total.

5.5 Costs of Hg emission reduction

Mercury is released to the environment from a variety of sources. Consequently, a number of different options are available to reduce emissions.

Abatement of mercury from by-product sources

In terms of monetary cost, reducing Hg from coal combustion and other industrial processes is dependent on a variety of factors. The cost varies substantially depending on factors such as the type of coal used, the type of combustion unit, the type of control devices already in place to control other pollutants, the facility configuration, and the percent reductions expected. For example, wet scrubbers installed primarily for Hg have been estimated to cost between US$ 76,000 and US$ 174,000 per pound of Hg removed (as discussed in Kraus et al., 2006). This result is very close to the cost of 150,000 € (US$ 220,000) per kg of Hg removed, estimated and used in a study of the effectiveness of the UN ECE heavy metals (HM) Protocol and cost of additional measures (Visschedijk et al., 2006). This cost is a marginal cost for Hg and it relates primarily to the application of electrostatic precipitators (ESPs) in combination with wet scrubbers. Based on Varian (1992) where minimum average cost occurs at the point where average cost and marginal cost are equal, the marginal costs used in the calculations are minimum average costs. Another study reviewing the costs for strategies to avoid Hg pollution and their emission reduction potential has been carried out by Hylander and Goodsite (2006). A summary of this work is presented in Appendix 4. The information presented in Kraus et al. (2006) and Visschedijk et al. (2006) is within the cost ranges of costs indicated in this Appendix.

When more advanced removal technology will be in place, including the sorbent injection in addition to the combination of ESPs/ FFs and FGD (the MFTR scenario), then the Hg removal costs will be higher. On the basis of information presented in the UNEP GLOMER project (UNEP, 2008), the cost of Hg removal within the MFTR scenario would be around US$ 330,000 per kg of Hg removed in the developed regions and US$ 220,000 per kg of Hg removed in the developing regions.

The above mentioned Hg removal costs vary not only with respect to the regions but they are also differing for emission source categories. The cost of 150,000 € (US$ 220,000) per kg of Hg abated was estimated for combustion of coal in power plants. This cost is a bit higher for industrial combustion (168,000 € or US$ 250,000 per kg Hg abated) and a bit lower for cement industry (144,000.00 € or US$ 210,000 per kg Hg abated), as reported in Visschedijk et al. (2006).

Actual costs of abatement would also be affected by the policy to be implemented in order to achieve the proposed reductions. See also discussion on co-benefits in Section 5.6.

Cost of abatement equipment on Best Available Technology (BAT) level (ESPs + FGD) contributes less than 5 % of the total coal-fired power plant costs (without fuel costs). If the cost of coal is included in the cost of the plant, this contribution is at a level of 3-3.5 %. The basis for the estimation is derived from (Rokke, 2006) for the production cost of a new coal plant of 40 € (60$) per MWh, including a fuel cost of 9,4 € (14,1 $) per MWh, together with a total cost of BAT technique of 1,52 € (2,28$) per MWh.

The cost of abatement can potentially differ for the different parts of the word due to operational costs dependent on labour costs etc. However, it seems like the price of energy is more relevant to regional differences. It is therefore not attempted to differentiate the level of abetment costs between industrialized and less developed countries in this study.

Costs of reducing the intentional use of mercury

Intentional use of Hg comprises a number of different categories with different use patterns, potentials for reduction of use and associated costs. A qualitative assessment of costs and benefits of different abatement strategies was presented in UNEP (2008).

Abatement strategies and cost assessments for intentional use of Hg are to some extent more complex than those relevant for by-product emissions from e.g. coal combustion. For instance, if Hg consumption is reduced, costs will appear as reduced income for producers and Hg traders, the manufacturer of products with Hg or industry where Hg is used in the process and finally consumers of a potentially more expensive Hg-free product. On the other hand, increased income for control technology producers and producers of Hg-free products would be expected. It would thus be relevant to evaluate the potential costs in reducing Hg consumption in a sequence from production to final consumption. Based on UNEP (2006) the main sources of Hg on the global market in year 2005 are presented in Table 13.

Table 13: Sources of mercury supply (2005)

Sector	Mercury supply (metric tonnes) Range
Primary mercury mining	1350–1600
By-product mercury	450–600
Recycled mercury from chlor-alkali wastes	90–140
Recycled mercury - other	450–520
Mercury from chlor-alkali cells (decommissioning)	600–800
(Stocked)	0–200
Total	3000–3800

Abatement alternatives for Hg in Artisanal and Small-scale Gold Mining (ASGM) were discussed in UNEP (Pacyna et al., 2008). One of the main conclusions is that this activity is poverty driven and major reductions can only be expected if the general economic development allows it and if alternative means of income are available. Reducing the global availability and/or market prices of Hg may have a positive influence mainly by encouraging reduced consumption and recycling of Hg. However, there are also simple and low-cost technological measures which, in combination with education and awareness raising, can reduce consumption of Hg significantly.

Reducing of Hg use in products comprises different product categories but they have in common that a feasible abatement strategy is the substitution of a Hg containing product to a Hg free product. For many categories, substitution can be achieved with no or very small additional costs since substitutes to Hg-containing products are already established on the market (batteries, dental applications, measuring and control equipment, electric and electronic devices). Although this may not be the case for products where substitutes for Hg are unavailable or scarce (e.g. low energy lamps). In that case, reduction of Hg use would be more expensive.

In UNEP (Pacyna et al., 2008), options for controlling Hg emissions from Chlor-Alkali (CA) industry were discussed. Here it was assumed that a technology switch to membrane or other Hg-free technology is the main alternative, although significant emission reductions can be achieved via process management.

In general, the costs associated with reduced trade of Hg and substitution of Hg containing products and or industrial processes are most likely significantly lower per kg of Hg than costs of end-of-pipe solutions for the by product emissions discussed above. A thorough evaluation of the resulting emission reductions and the potential benefits of reducing use of Hg in e.g. a specific group, is however needed before a direct comparison can be made.

5.6 Discussion

The benefits for society that would result from reduced emissions of Hg involve a number of health effects (as has been presented previously in this report) as well as a number of environmental effects. It is important to remember that the benefit on IQ-levels presented in this report is only a sub-effect of all the benefits associated with reduced Hg pollution. Unfortunately this is the only properly monetized damage cost from Hg pollution, but we are aware that there are a number of other damages from Hg pollution that would need to be monetized in order to give a complete quantitative picture of the damage costs related to Hg pollution.

For a full analysis of societal costs and benefits, several aspects of Hg pollution, sources, impacts and co-benefits need to be considered. Furthermore, it is of great importance to analyze to what extent human health impacts other than IQ loss, and environmental impacts has on the social benefit estimates. Since most studies dealing with these benefits are locally oriented (with local conditions), it is difficult to extrapolate these results to global or larger regional scales. It is also necessary to discuss which type of benefits to include. This will be dependent of the availability of relevant information. For instance, as discussed above, applying the more complete description of health benefit as presented by Rea and Graham (2004) study, the resulting benefits were 7 times higher than the benefit estimated for IQ changes alone (as used in this study).

The willingness-to-pay (WTP) study conducted for Chesapeake Bay area (Hagen et al., 1999) can be used to represent the preferences of the world population after being adjusted for the differences in purchasing power between the USA and the world. Extrapolation from WTP estimates for 5, 12, 21 and 35 percent reduction indicates that households would be willing to pay about 270 US$ for a 50 % reduction of deposited Hg, like in the EXEC scenario. The average household size in the study was 2.6 persons. This implies that the average WTP for 50 % reduction is 104 US$ per person for the EXEC scenario and 119 for the MFTR scenario. The purchasing power in the world is 0.2278 of that in the USA (UNDP, World Development Report 2007/8). The average WTP in the world would be 24 US$/person for the EXEC scenario and 27 for the MFTR scenario, if the Hagen et al. study is representative after corrections. There are 6741 persons in the world. The global societal benefits for the environment is thus 159 billion US$ for the EXEC scenario and 183 for the MFTR scenario, The resulting values from our estimate on damage costs due to IQ-loss and when taking into account the assumptions derived in the literature, can be seen in Figure 16.

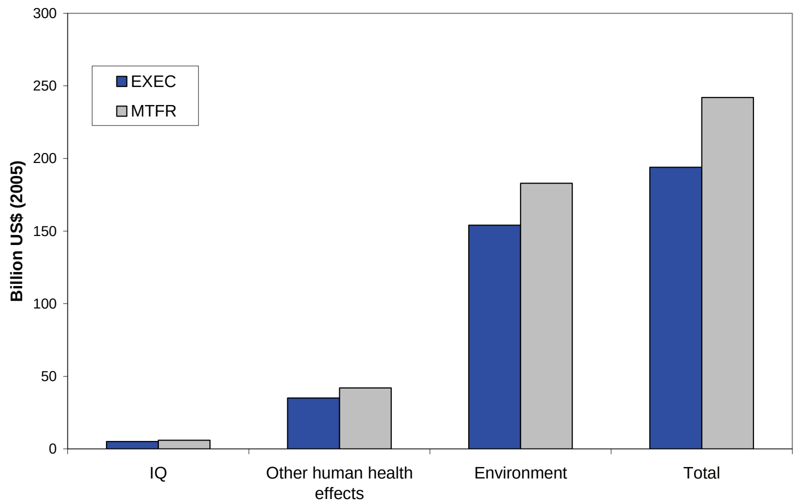

Figure 16. Estimated total societal benefits (billion 2005 US$) (see text below for definitions).

The Societal benefits of reducing IQ-loss are estimated from this study. This estimate is multiplied with 7 to meet the assumptions made from the (Rea and Graham, 2004) study and is referred to as other human health effects in Figure 16. If we at the same time take into account the results from the (Hagen et al.,1999) study for estimating the societal benefits on the environment, the total estimate for benefits from the EXEC and MFTR scenarios are 194 and 242 billion US$, respectively.

From these results, it is evident that the size of the benefits of reducing Hg emissions varies greatly with varying assessment approaches and with varying scope of the studies. The damage costs presented in this study are thus most likely underestimated since only the damage costs related to IQ loss were considered. A thorough analysis of several aspects of these calculations would need to be made before application to a quantitative cost benefit assessment.

In the analysis of benefits of reducing emissions from intentional use of Hg, many of the estimated numbers used in the analysis are uncertain. Nevertheless, these emission reductions can probably be achieved at a relatively low cost in comparison to reduction of emissions from e.g. coal fired power plants.

There are a number of co-benefits related to the Hg emission reduction from by product emission sources. The control technologies used to reach the emission levels stipulated in the scenarios are almost all multi-pollutant emission reducing technologies, except for the most expensive ones. Following large reductions in mercury emissions from coal power plants there will be large emission reductions of Particulate Matter (PM) and sulphur dioxide (SO_2). PM is established as related to lung and cardiovascular deceases (Sjöberg et. al 2008) and SO_2 is since long established as the main precursor of acidification and corrosion of buildings.

In coping with the Hg emissions for the by-product emissions, ESPs and FFs installed and sulphur compounds also reduce emission of fine particles. In fact, it is more likely that a technology is introduced in order to deal with other, quantitative larger substances rather than dealing with Hg alone.

For Europe (which has already reduced much of SO_2 emissions), the benefit/cost ratio for introducing best available technologies for SO_2 removal at the 100 largest coal power plants is 3.4, even though it only accounts for health effects. The techniques introduced are to a large extent identical to the techniques used to reduce Hg emissions (Barrett & Holland 2008).

From the EU DROPS project, it assessment was presented on the costs and benefits of the abatement of the heavy metals As, Cd, Hg, Ni and Pb in addition to PM2,5 for the four case countries Poland, Czech Republic, Germany and Norway in the socio-economic development scenario i.e. Business As Usual with climate policies (BAU+climate) (similar to the EXEC scenario in the UNEP-GLOMER project) for the year 2020. As benefits from the reduction of both the heavy metals and the PM2,5 were included in the DROPS study; the benefits exceeded by far the abatement costs of the installed technology. The study also showed that the co-benefits were large compared to the benefits for Hg alone. For instance for Germany, the isolated beneficial effect on Hg were estimated to be 42 million Euros (63 million US2000$) per year in 2020 while the co-benefits were as high as 11,5 billion Euros (17 billion US2000$) per year, where PM2,5 (inhalation) was responsible for 92 % of the value.

6. Conclusions

This study contains an analysis of the damage costs of continuing mercury pollution without any further measures until 2020. The analysis has mainly focussed on IQ losses due to the exposure to methyl mercury via ingestion of contaminated fish. Other human health, social and environmental damages are also discussed as are costs of controlling mercury emissions. Furthermore, societal benefits of reducing mercury emissions are presented for two emission reduction scenarios.

The main conclusions are:

- Global emissions of mercury to the atmosphere in 2020 have been estimated for three scenarios; Status Quo (no further actions to control mercury) 2 439 tonnes; EXEC (Extended Emission Control) 1 213 tonnes and MFTR (Maximum Feasible Technical Reduction) 946 tonnes. The corresponding emission for year 2005 were previously estimated to 1 958 tonnes.
- If no further action is taken to reduce mercury emissions globally (the SQ scenario), loss of IQ will lead to annual damage costs of 8 Billion 2005 US$ for emissions from by-product sources. The corresponding number for emissions from intentional use of mercury is 2 Billion 2005 US$. The total damage costs to society of mercury pollution are likely to be considerably higher since a complete set of potential costs to society was not taken into account.
- Already identified sensitive regions such as the Arctic will continue to be affected. Based on a simple evaluation of emission/deposition patterns of mercury and global fisheries data, Australia/Oceania, parts of South America and South East Asia were indicated as regions with high potential risk of negative impacts and thus large damage costs. It should be noted that these estimates only takes into account potential exposure and impacts caused by atmospheric emissions and long-range transport of mercury. Local use and emissions of mercury from e.g. artisanal gold mining, improper waste handling, product use etc may give rise to exposure risks with different geographical patterns.
- With introduction of policies to reduce emissions according to two scenario calculations, the emissions can be reduced by around 50% and 60% for the EXEC and MFTR scenarios, respectively, in comparison to the SQ scenario. The annual damage costs can be reduced significantly leading to benefits of approx. 5 billion US$ and 6 billion US$ for the two different emission scenarios, respectively.

- There are a number of co-benefits related to the Hg emission reduction from by product emission sources. The control technologies used to reach the emission levels stipulated in the scenarios are almost all multi-pollutant emission reducing technologies, except for the most expensive ones. Following large reductions in mercury emissions from coal power plants there will be large emission reductions of Particulate Matter (PM), sulphur dioxide (SO_2) and other pollutants.

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Sammanfattning

(Summary in Swedish)

Kvicksilver frigörs från en rad olika källor inklusive energiproduktion, industriella tillämpningar samt produktion, användning och omhändertagande av produkter som innehåller kvicksilver. Kolförbränning är den viktigaste emissionskategorin. På global nivå bidrar Asien med mer än 40% av de globala utsläppen. På grund av sina kemiska och fysikaliska egenskaper, kan kvicksilver spridas globalt via atmosfären och många avlägsna ekosystem har påverkats av detta giftiga ämne.

Kvicksilver finns i miljön i olika former av vilka den mest giftiga är metylkvicksilver. Detta är också den form som bioackumuleras i akvatiska näringskedjor. Konsumtion av fisk är således den viktigaste exponeringsvägen för människa. Sammanställningar har visat att en betydande andel av världens människor och ekosystem utsätts för metylkvicksilver på för höga nivåer.

I ett samhällsekonomiskt perspektiv orsakar kvicksilverföroreningar kostnader för samhället exempelvis som skadekostnader för negativa effekter på människors hälsa och miljön, förlust av inkomst från minskat kommersiellt fiske, administrativa kostnader för vetenskaplig forskning och utveckling, kontroll och riskkommunikation.

Den allvarligaste effekten på människors hälsa av den globala kvicksilverspridningen är neurologiska skador som leder till försämrad utveckling av hjärnan, om exponering sker under graviditeten dvs. om gravida kvinnor äter mat förorenad med metylkvicksilver. Den försämrade utveckling av hjärnan leder till en förlust av IQ (Intelligence quotient) poäng. Andra toxikologiska effekter omfattar ökad risk för hjärtkärlsjukdomar. De skadekostnader som kan uppkomma genom förlusten av IQ innefattar t.ex. inkomstförluster och kostnader för minskade möjligheter att tillgodogöra sig utbildning.

I denna studie har kostnader för skador på människors hälsa gällande förlust av IQ orsakat av kvicksilver bedömts för globala utsläpp till luft enligt ett status quo (SQ) scenario. För detta scenario antogs att inga ytterligare åtgärder vidtas för att kontrollera kvicksilverutsläpp under perioden 2005 till 2020. Status quo scenariot innefattar en ökning av den ekonomiska tillväxten och därmed ökade utsläpp av kvicksilver från biprodukt källor (där kvicksilver förekommer som en förorening), t.ex. energiförbrukning och industriella processer. Enligt scenariot kommer utsläppen att öka med ca 25% mellan 2005 och 2020 för både emissioner från biprodukt källor och avsiktlig användning av kvicksilver.

De årliga skadekostnaderna för intag av metylkvicksilver beräknades till ca. 8 miljarder 2005 US$ för biprodukt utsläpp och 2 miljarder 2005 US $ för utsläpp från avsiktlig användning av kvicksilver i SQ scenario 2020. Motsvarande skadekostnader för inandning av kvicksilver uppskattades till 2,9 miljoner 2005 US $ dvs. en bråkdel av kostnaderna orsakade av förtäring av förorenad fisk. Dessa resultat gäller för världens befolkning generellt. För vissa befolkningsgrupper som t.ex. arbetar med småskalig guldutvinning kan exponering via inandning förorsaka allvarliga hälsoproblem och därmed stora skadekostnader.

Den totala skadekostnaden för samhället orsakade av kvicksilverspridningen är sannolikt betydligt högre än detta eftersom denna studie endast innefattade kostnader för skador på IQ orsakade av konsumtion av förorenad fisk.

Utöver SQ scenariot, så har skadekostnader för två andra scenarier beskrivna i UNEP: s rapport om globala antropogena utsläpp av kvicksilver (2008) diskuterats: Extended Emission Control (EXEC) och Maximum Feasible Technical Reduction (MFTR). I dessa scenarier, antas en högre grad av kontroll av utsläpp vilket resulterar i en minskning av de totala utsläppen på 50% respektive 60%, under perioden 2005–2020. Den motsvarande årliga nyttan definierat som minskade skadekostnader uppskattas till cirka 5 och 6 miljarder US-dollar för EXEC och MFTR scenarierna.

Beräkningarna visar tydligt att stora vinster kan uppnås genom att minska de globala utsläppen av kvicksilver. Samverkansfördelar av flera åtgärder som inte bara kontrollerar utsläppen av kvicksilver men även t.ex. partiklar, svaveloxid och kväveoxid, förväntas vara betydande när det gäller t.ex. kolförbränning.

Kvicksilverföroreningar kan potentiellt påverka människor över hela världen. En mängd information finns avseende föroreningsnivåer och potentiella effekter i t.ex. nordiska länderna, Nordamerika och Arktis. Baserat på en bedömning av den globala fiskkonsumtionen i kombination med modellerat globalt nedfallsmönster av kvicksilver, så har Australien/Oceanien, delar av Sydamerika och Sydostasien identifierats som tillkommande områden med potentiellt höga risker för kvicksilver påverkan och därmed skadekostnader av negativa effekter på människa och miljö. Det bör poängteras att denna geografiska bedömning är baserad på risker kopplade till konsumtion av fisk förorenad av långdistanstransporterat kvicksilver. I andra regioner kan effekter av kvicksilverexponering vara större från t.ex. småskalig guldutvinning och hantering av kvicksilverinnehållande avfall.

Appendix 1

Methodology for Global intake of MeHg and damage costs assessment by Spadaro and Rabl (2008) used and presented in the EU DROPS project (Scasny et al., 2008)

The best understood health impacts of mercury are neurotoxic. The most important studies on neurotoxic impacts have followed cohorts of children among three populations (in New Zealand, the Seychelles, and the Faroe Islands) whose diet contains a particularly large portion of seafood; here significant associations between exposure and neurotoxic impacts have been observed. For instance, based on these findings, Trasande et al. (2005) consider several possible forms of the DRF with and without threshold effect in estimating the social cost of the IQ decrement in the USA. These DRFs are then revised in Trasande et al 2006. Revised function of DRFs for Hg by Axelrad et al. (2007) is based on an integrative analysis of the New Zealand, the Seychelles, and the Faroe Islands studies and Trasende et al. estimates. This function is also used in Spadaro and Rabl (2008) study.

The impacts are relevant for children due to the transmission of toxic substance eaten by pregnant mother. Regarding the impacts among adults, no significant association with neurotoxic impacts was found due to the less sensitiveness of the adult brain (Weil et al., 2005).

In fact, a pathway of mercury through the environment is very complex and requires very complex modelling. DROPS can hardly apply complex global modelling to estimate changes in intake of MeHg by the individual(-s) due to release of unit of emission of mercury. We follow therefore here a simplified approach developed by Spadaro and Rabl (2004; 2008). Particularly their 2008 study presents the first estimate of global average neurotoxic impacts and 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 as MeHg on its way to the ultimate environmental sink, mostly ocean sediments…" (Spadaro and Rabl 2008).

Following step in the impact assessment by Spadaro and Rabl is derivation of the slope factor, i.e. number of IQ point losses due to daily (yearly) intake of MeHg. Slope factor 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. As the final product, the slope factor s_{DR} is 0.036 IQ points per µg/day.

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

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

where D_{th} is the threshold dose.

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

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

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

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

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

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

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

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

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

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

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

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

Work loss years can be calculated as

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

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

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

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 $t \neq 18$.

Total impact, i.e. IQ points, and total damage costs per kg of mercury are assuming the schooling effect as derived by Salkever, i.e. 0.1007 years per IQ point

	IQpoints	Damage costs
with the treshold of 6.7 µg/day	0.82	5,285 €
without the threshold	1.88	10,950 €

Appendix 2. Definitions of EXEC and MFTR Scenarios for by-product sources

The type and efficiency of technological and non-technological measures to reduce emissions of mercury from sources are reviewed in the UNEP-CBA project (Pacyna et al., 2008). A number of technical and non-technical measures are available for reducing the Hg emissions from: i) anthropogenic sources where Hg is a by-product (e.g. power plants, smelters, cement kilns, other industrial plants), ii) various uses, and iii) waste disposal. These measures differ with regard to emission control efficiency, costs, and environmental benefits obtained through their implementation. Very often Hg emissions are substantially reduced by equipment employed to reduce emissions of other pollutants. The best example is the reduction of Hg emissions by the flue gas desulfurization (FGD) installations. Removal efficiency of FGD installations for mercury ranges from 30 to 50%. The same applies to de-NOx installations, and control devices reducing emissions of fine particles.

Higher Hg emission control efficiencies, exceeding 95 %, can be obtained through a combination of FGD and electrostatic precipitators (ESPs) or fabric filters (FFs) with "add on" type of equipment, specific for removal of mercury from the flue gases, including carbon filter beds and activated carbon injection. However, the combined solutions are very expensive and used only at a few sites around the globe.

The development of two scenarios projecting the application of technological and non-technological measures of Hg emission reductions, namely the EXEC and MFTR scenarios defined in the Introduction to this report, has been done within the UNEP-GLOMER project (UNEP, 2008). The assumptions made for these scenarios with respect to major source categories are presented in the Table below. It should be added that the EXEC and MFTR scenarios project changes of emissions only for sources where mercury is emitted as a by-product (no emissions from mercury uses included).

Assumptions for the 2020 EXEC and MFTR emission scenarios for mercury

Sector	EXEC	MFTR
Large combustion plants	Dedusting: fabric filters and electrostatic precipitators operated in combination with FGD.	Dedusting installations combined with FGD and sorbent injection. In 2020 20% of electricity and heat produced from renewable sources.
Iron and steel production	In sintering: fine wet scrubbing systems or fabric filters with addition of lignite coke powder, catalytic oxidation. In blast furnaces: scrubbers or wet ESPs for BF gas treatment. In basic oxygen furnace: dry ESPs or scrubbing for primary dedusting and fabric filters or ESPs for secondary dedusting. In electric arc furnaces: fabric filters.	Sorting of scrap. New iron-making techniques. Direct reduction and smelting reduction.
Cement industry	Dedusting: fabric filters and electrostatic precipitators at all plants.	All plants with advanced techniques for metals reduction.

Appendix 3

Damage costs due to IQ-loss from ingestion and inhalation for the EXEC and MFTR scenarios. Results for continents and by-product source category

EXEC 2020									
Ingestion, in million US$	**Coal con-sump-tion**	**Crude petroleum consump-tion**	**Cement produc-tion**	**Metals produc-tion**	**Large-scale gold produc-tion**	**Mercury produc-tion**	**Waste incine-ration**	**Other sources**	**Total**
Region									
Africa	87.0	3.6	50.9	4.3	135.6	0.0	0.4	0.0	281.8
Asia (excl. Russia)	1172.1	28.0	149.0	162.9	100.6	15.4	0.8	1.0	1629.6
Austra-lia/Oceania	92.6	1.8	1.8	30.7	91.8				218.8
Europe (excl. Russia)	286.4*		67.0	66.9			18.4	102.1	540.8
North America	440.9	5.5	51.4	85.0	203.0	0.0	50.5	102.4	938.8
South America	13.1	3.1	9.0	21.7	46.4			6.9	100.2
Russia	94.5	4.1	8.3	14.7	20.8	0.0	3.5	7.2	153.2
Total	**2186.8**	**46.0**	**337.4**	**386.0**	**598.2**	**15.5**	**73.6**	**219.7**	**3863.1**

EXEC 2020									
Inhalation, in thousand US$	**Coal con-sump-tion**	**Crude petroleum consump-tion**	**Cement produc-tion**	**Metals produc-tion**	**Large-scale gold produc-tion**	**Mercury produc-tion**	**Waste incine-ration**	**Other source s**	**Total**
Region									
Africa	24.6	0.8	6.2	2.0	11.1	0.0	0.2	0.0	44.9
Asia (excl. Russia)	682.8	8.3	77.9	66.7	76.5	11.4	0.6	0.7	924.9
Australia/Oceania	17.1	0.2	0.3	5.7	19.5				43.0
Europe (excl. Russia)	103.2*		17.6	15.5			4.5	31.2	172.1
North America	64.5	1.2	8.8	13.3	28.4	0.0	7.3	14.5	138.1
South America	5.1	1.2	3.6	7.7	20.8			2.0	40.4
Russia	25.2	1.1	2.2	3.9	5.5	0.0	0.9	1.9	40.8
Total	922.5	12.8	116.6	114.8	161.8	11.4	13.5	50.3	1404.2

*Includes oil combustion and residential combustion

MFTR 2020 Ingestion, in million US$ Region	Coal consumption	Crude petroleum consumption	Cement production	Metals production	Large-scale gold production	Mercury production	Waste incineration	Other sources	Total
Africa	63.5	2.6	37.1	3.1	135.6	0.0	0.3	0.0	242.2
Asia (excl. Russia)	1192.8	20.4	108.7	118.8	100.6	15.4	0.5	1.0	1220.3
Australia/Oceania	160.0	1.3	1.3	22.4	91.8				184.4
Europe (excl. Russia)	241.0*	0.0	48.9	48.8	0.0	0.0	13.4	102.1	454.1
North America	321.6	4.0	37.5	62.0	203.0	0.0	36.8	102.4	767.4
South America	9.6	2.2	6.6	15.8	46.4			6.9	87.5
Russia	69.0	3.0	6.0	10.7	20.8	0.0	2.6	7.2	119.3
Total	**2057.4**	**33.6**	**246.1**	**281.6**	**598.2**	**15.5**	**53.7**	**219.7**	**3075.4**

MFTR 2020 Inhalation, in thousand US$ Region	Coal consumption	Crude petroleum consumption	Cement production	Metals production	Large-scale gold production	Mercury production	Waste incineration	Other sources	Total
Africa	17.9	0.6	4.5	1.5	11.1	0.0	0.1	0.0	35.8
Asia (excl. Russia)	498.1	6.1	56.8	48.6	76.5	11.4	0.4	0.7	698.6
Australia/Oceania	12.5	0.2	0.2	4.2	19.5				36.6
Europe (excl. Russia)	90.3*		12.8	11.3			3.3	31.2	148.9
North America	47.1	0.9	6.4	9.7	28.4	0.0	5.3	14.5	112.3
South America	3.7	0.9	2.6	5.6	20.8			2.0	35.6
Russia	18.4	0.8	1.6	2.8	5.5	0.0	0.7	1.9	31.8
Total	688.0	9.5	84.9	83.7	161.8	11.4	9.8	50.3	1099.6

*Includes oil combustion and residential combustion

Appendix 4.

Costs for strategies avoiding Hg pollution and their potential to reduce Hg pollution, expressed in classes: small, medium, and large (after Hylander, l. D., Goodsite, M. E., 2006, Environmental costs of mercury pollution, Science of the Total Environment 368 (2006) 352–370)

Costs for strategies avoiding Hg pollution and their potential to reduce Hg pollution, expressed in the classes: small, medium, and large

Activity	Place and year	Cost[a] (US$ kg^{-1} Hg)	Reduction potential	Reference
Return of Hg thermometers	Sweden, 1992–1996	950–1200[b]	Large	Rein and Hylander, 2000
Replace mercury-containing items	Minnesota, estimated 1999	20–2000[c]	Large	Jackson et al., 2000
Collect Hg and Hg compounds in school labs	Sweden, 1995–1999	70–400[b]	Small	Rein and Hylander, 2000
Collect metallic Hg in school laboratories	Minnesota, estimated 1999	20[c]	Large	Jackson et al., 2000
Collect Hg compounds in school laboratories	Minnesota, estimated 1999	1400[c]	Small	Jackson et al., 2000
Replacing Hg cells at chlor–alkali plants	USEPA, estimated 1996	10 100[d]	Large	USEPA, 1997
Increase recycling of chairside traps in dentistry	Minnesota, estimated 1999	240	Medium	Jackson et al., 2000
Install amalgam separators	Minnesota, estimated 1999	33 000–1 300 000	Medium/Large	Jackson et al., 2000
Replace dental amalgam fillings at dentists	Sweden, estimated 2004	129 000	Large	This study
Remove dental amalgam fillings at death	Sweden, estimated 2004	400	Large	This study
Flue gas cleaning with carbon at crematoria	Sweden, estimated 2004	170 000–340 000	Medium/Large	This study
Flue gas cleaning with carbon at crematoria	UK, estimated 2004	29 000	Medium/Large	This study, BBC News, 2005
Medical waste incinerators with scrubber	USEPA, estimated 1996	4400–8800	Medium/Large	USEPA, 1997
Carbon injection into flue gases at waste incinerators	USEPA, estimated 1996	465–1900	Medium/Large	USEPA, 1997
Combined technologies at waste incineration	Uppsala, Sweden, 2004	40 000	Large	This study
Coal cleaning, conventional, chemical or both	Minnesota, estimated 1999	100 000–128 000	Large	Jackson et al., 2000
Carbon injection into flue gases at power plants	USEPA, estimated 1996	31 000–49 000[e]	Large	USEPA, 1997
–"–	US Dep. Energy, estimated 1996	149 000–154 000[e]	Large	Brown et al., 2000
–"–	Minnesota, estimated 1999	20 000–725 000	Large	Jackson et al., 2000
Combined technologies at power plants	USEPA, estimated 1996	11 000–61 000[e]	Large	USEPA, 1997
–"–	US Dep. Energy, estimated 1996	56 000–85 000[e]	Large	Brown et al., 2000
Wind as replacement for energy from coal	Minnesota, estimated 1999	1 200 000–2 000 000	Large	Jackson et al., 2000

[a] Values in a range reflect differences across facilities of different sizes or at different recovery rates e.g. 90% or >95% of Hg recovered from flue gases, or other site-specific conditions.

[b] Cost calculated per kilogram Hg collected and includes costs for information, reimbursement for thermometers, and additional costs for collecting, transport and deposition, while costs for additional working time of shop assistants, municipal officials, etc. are excluded.

[c] Total cost per unit of Hg not emitted.

[d] Capital and electrical costs. Indirectly reduced Hg emissions caused by lower consumption of electricity from Hg emitting power plants have not been included. The costs increase if pollution occurred earlier needs extensive remediation.

[e] 90% reduction in mercury emissions. The EPA figures are based on a lower flue gas temperature when carbon is injected, thereby using the sorption capacity better, resulting in that only 2–34% active carbon is used compared to the DOE estimates.