Journal of Cleaner Production 18 (2010) 386–394

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Economic benefits from decreased mercury emissions: Projections for 2020

Kyrre Sundseth [a,*], Jozef M. Pacyna [a,b], Elisabeth G. Pacyna [a], John Munthe [c], Mohammed Belhaj [c], Stefan Astrom [c]

[a] NILU – Norwegian Institute for Air Research, Center for Ecology and Economics, PO Box 100, NO-2027 Kjeller, Norway
[b] Faculty of Chemistry, Gdansk University of Technology, Gdansk, Poland
[c] IVL Swedish Environmental Research Institute, PO Box 5302, 400 14 Gothenburg, Sweden

ARTICLE INFO

Article history:
Received 26 June 2009
Received in revised form
19 October 2009
Accepted 20 October 2009
Available online 5 November 2009

Keywords:
Mercury
Costs
Benefits
Global emissions
Future scenarios

ABSTRACT

Anthropogenic processes have increased the exposure of humans and wildlife to toxic methyl mercury (MeHg). Mercury emissions will increase by about 25% between 2005 and 2020, if the present trajectory is maintained. A global assessment of societal damages caused by the ingestion of methyl mercury, based merely on loss of IQ (Intelligence Quotient), suggests that the annual cost will be approximately US$3.7 billion (2005 dollars) in 2020. The corresponding cost of damages resulting from the inhalation of methyl mercury is estimated at US$2.9 million (2005 dollars). Under a higher degree of emission control such as in the case of the Extended Emission Control (EXEC) and the Maximum Feasible Technological Reduction (MFTR) scenarios, total emissions could decrease in the period 2005–2020 by about 50–60%. The corresponding annual benefits in 2020 are estimated to be about US$1.8–2.2 billion (2005 dollars). Large economic benefits can be achieved by reducing global mercury emissions.

1. Introduction

Mercury (Hg) is causing significant environmental damage worldwide. International agreements and cooperation are needed to cope with the consequences of the environmental and human health impacts caused by mercury contamination. In this context, mercury has been on the agenda of the United Nations Environmental Programme's (UNEP) Governing Council (GC) since 2002. A part of the UNEP initiative is to obtain the best available information on atmospheric mercury emissions and trends, as well as to investigate applicable regulatory mechanisms. A global inventory of anthropogenic emissions to the atmosphere in 2005 was prepared by UNEP Chemicals and Arctic Monitoring Assessment Programme (AMAP) as a contribution to the UNEP report; *Global Atmospheric Mercury Assessment: Sources, Emissions and Transport* [1]. Mercury emissions and emission trends by country, region and sector were assessed, and the anthropogenic emissions estimates were geospatially distributed. Scenario emissions inventories for 2020 were also compiled on a global scale to investigate the implications of actions to reduce mercury emissions (the 'Status Quo' (SQ) scenario, the 'Extended Emissions Control' (EXEC) scenario, and the Maximum Feasible Technological Reduction' (MFTR) scenario).

The 2020 SQ emission scenario assumes that current practises and abatement techniques in controlling mercury emissions from various sources and uses of mercury that result in mercury emissions to the atmosphere will continue until the year 2020 (i.e. that in the year 2020 production of anthropogenic mercury emissions will proceed without additional legislation or control as in the year 2005). The EXEC scenario, on the other hand, assumes economic progress at a rate dependent on the future development of industrial technologies and emissions control technologies – that is, that the mercury-reducing technology currently generally employed throughout Europe and North America would be implemented elsewhere. It further assumes that emissions control measures currently implemented or committed to be implemented in Europe to reduce mercury emissions to air or water would be implemented around the world. These include certain measures adopted under the LRTAP Convention, EU Directives, and also agreements to meet the IPCC Kyoto targets on reduction of greenhouse gases that will cause reductions in mercury emissions. Finally, the MFTR scenario assumes implementation of all available solutions/measures, leading to the maximum degree of reduction of mercury emissions and its discharges to any environment; cost is taken into account but only as a secondary consideration. Table 1 summarizes the assumptions made for mercury for the year 2020 [1].

* Corresponding author. Tel.: +47 63 89 82 22.
E-mail address: kyrre.sundseth@nilu.no (K. Sundseth).

0959-6526/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2009.10.017

Table 1
Scenario assumptions made for mercury for the year 2020 (as presented in the UNEP assessment [1]).

Sector	SQ 2020	EXEC 2020	MFTR 2020
Large combustion plants	Increase in coal consumption in Africa (20%), South America (50%) and Asia (50%). Application of current technology.	SQ 2020 plus: De-dusting: fabric filters and electrostatic precipitators operated in combination with FGD. Activated carbon filters. Sulphur-impregnated absorbents. Selenium impregnated filters.	SQ 2020 plus: Integrated gasification combined cycle (IGCC). Supercritical polyvalent technologies. 50% participation in electricity generation by thermal method.
Iron and steel production	Application of current technology.	In sintering: fine wet scrubbing systems or fabric filters (FFs) with addition of lignite coke powder. In blast furnaces: scrubbers or wet ESPs for BF gas treatment. In basic oxygen furnace: dry ESP or scrubbing for primary de-dusting and fabric filters or ESPs for secondary de-dusting. In electric arc furnaces: fabric filters and catalytic oxidation.	EXEC 2020 techniques in existing installations plus: Sorting of scrap. New iron-making techniques. Direct reduction and smelting reduction.
Cement industry	Increase in global cement production (50%).	SQ 2020 plus: De-dusting: fabric filters (FFs) and electrostatic precipitators (ESP).	SQ 2020 and EXEC 2020 plus: All plants with techniques for heavy metals reduction.
Chlor-alkali industry	Application of current technology.	Phase-out of mercury cell plants by 2010.	

Mercury emission scenarios have recently been made by Streets et al. for 2050 based upon IPCC (Intergovernmental Panel on Climate Change) scenario assumptions. However, these are not further mentioned in this paper since they differ methodologically from the 2020 scenarios developed for the UNEP assessment, in terms of emission factors, technology, and economic parameters [2]. To develop cost-efficient strategies for reducing environmental and human health impacts, it is necessary to examine efficiencies and costs of available emission and exposure reduction options to mercury. Abatement techniques and practises employed to reduce emissions of mercury in the year 2005 are described in a report prepared for the UNEP Chemicals on the qualitative assessment of the potential costs/benefits associated with emission reductions of mercury from various sources [3].

However, a full economic 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 benefits for reducing the impacts on human health and ecosystems. Since such detailed information is lacking, a first step towards a full economic cost-benefit analysis was the merging of information on global anthropogenic mercury emissions [1] with societal costs of mercury pollution caused by negative impacts on human health in terms of intelligence quotient (IQ) decrement. The IQ loss is the only properly monetized damage cost due to methyl mercury (MeHg) exposure presented in the literature. This led to an assessment prepared for the Nordic Council of Ministers [4] where the societal damage costs of continuing the Status Quo of mercury pollution until 2020 were compared to the economic benefits of globally-introduced mercury emission controls assessed in the UNEP Chemical report [3]. The main outcome of this assessment is presented in this paper. Emphasis is placed on providing a conceptual understanding of the global mercury pollution problem caused by the different emission sources, economic costs from exposure, as well as economic benefits achieved from introducing mercury emission reduction measures in future emission scenarios.

2. Atmospheric mercury emission sources

Estimates of atmospheric emissions of mercury from major sources worldwide in the year 2005 are reported in the UNEP Chemicals Global Mercury Assessment [1]. Details on how the mercury emissions were estimated can also be found in Pacyna et al. [5]. Most of the anthropogenic mercury emitted to the atmosphere originates from mineral processing undertaken 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 [5]. The use of mercury in products may give rise to emissions during the production phase as well as during use and disposal. The major uses of mercury include: Chlor-alkali production using the mercury cell process, artisanal gold mining, amalgam use for dental services and production, use and disposal of mercury in products including batteries, measuring and control instruments, electrical lightning, wiring devices, and electrical switches [5].

The results of the anthropogenic emission estimates are presented in Fig. 1. About three quarters of the total anthropogenic emissions of mercury in the year 2005, estimated to be 1930 tonnes, comes from sources where mercury is emitted as a by-product (i.e. emissions generated unintentionally), with the remained is emitted during various applications of mercury. The

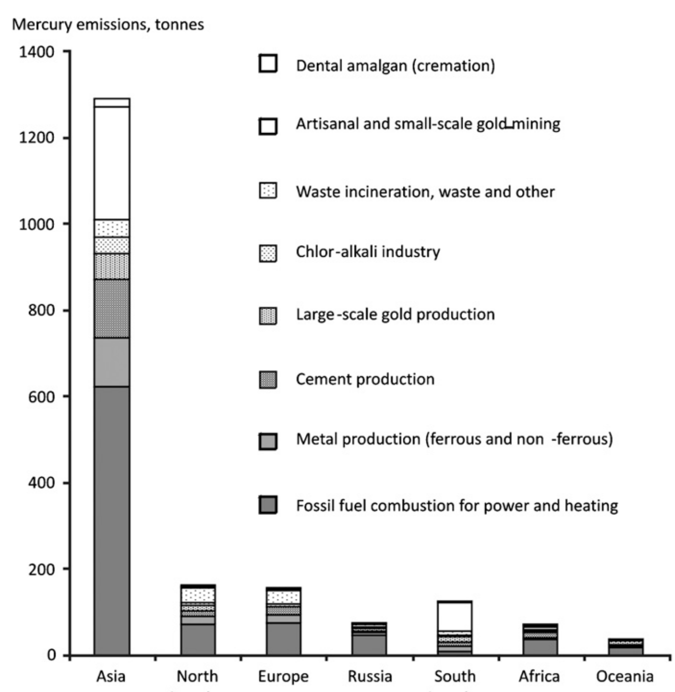

Fig. 1. Global anthropogenic emissions of mercury to air from different regions by sector in 2005. (From Pacyna et al. 2009 [5]).

largest share of mercury emissions to the global atmosphere (almost 46%) originates from the combustion of fossil fuels, mainly coal in utility, industrial, and residential boilers. These are followed by artisanal and small-scale gold mining (almost 18%); ferrous and non-ferrous metal production, including large-scale gold production (13%); and cement production, (about 10%).

Asia contributed the largest, as much as 60% of the total global mercury emissions. China, with more than 2000 coal-fired power plants and a host of other large mercury-emitting industrial activities, is the largest single emitter of mercury 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 [5]. Together, three countries – China, the USA and India – are responsible for about 55% of the total global mercury emissions from by-product sectors (i.e. 1480 tonnes).

3. Atmospheric mercury emissions: the status-quo scenario

The SQ scenario assumes that, in the year 2020, generation of anthropogenic mercury emissions will proceed without additional legislation or control as in the year 2005. The emission abatement techniques and practises employed to reduce emissions of mercury in the year 2005 are described in detail in the UNEP Chemicals report [3]. To summarize, the application of electrostatic precipitators (ESPs), fabric filters (FFs), and flue gas desulphurization (FGD) installations are taken into account for major point sources of mercury emissions to the atmosphere, such as large electric and heat generating power plants, non-ferrous and ferrous smelters, cement kilns and waste incinerators. It is assumed in the SQ emission scenario that the 2005 emission factors for these emission categories will not change until the year 2020.

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 was used to generate information needed within the CAFÉ (Clean Air for Europe) program (see http://europa.eu.int/comm/environment/air/cafe/index.htm).

Very little data are currently available to support the development of future scenarios to 2020 for mercury from product use, cremations of corpses with dental amalgam, and artisanal gold mining. Increased global supply and consumption of mercury 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 the product use of mercury, 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 mercury emissions substantially. For artisanal gold mining, the use of mercury is likely to continue or increase since this activity is driven mostly by poverty. Small-scale gold mining communities are dependent on the use of mercury for their livelihood and, as pointed out by Hilson [6], the dynamics of producing communities would have to be understood in order to resolve the mercury pollution problem. Even if mercury supply is decreased (e.g., via restricting export and trade from Europe), illegal trade may replace this mercury and new or previously active mercury mines may be reopened. For the SQ scenario, it has been assumed that the intentional use of mercury in the year 2005 will continue at the same level until the year 2020.

An increase of about 25% was estimated in 2020 compared to the 2005 estimate in the UNEP Chemicals study. The total anthropogenic mercury emissions to air in 2020 were estimated to be 2390 tonnes per year against 1930 tonnes in 2005 [1].

4. Reducing atmospheric mercury emissions beyond the Status Quo scenario

4.1. Mercury emission reduction measures in 2020

It was concluded in UNEP Chemicals [3] that a number of technical and non-technical measures are available for reducing mercury emissions from anthropogenic sources where mercury is a by-product (e.g. power plants, smelters, cement kilns, other industrial plants), is used intentionally, or used in waste disposal. These measures differ with regard to emission control efficiency, costs, and environmental benefits obtained through their implementation.

Mercury emissions may often be substantially reduced by equipment employed to reduce emissions of other pollutants. The best example is the reduction of mercury emissions using flue gas desulphurization (FGD) installations. The removal efficiency of FGD installations for mercury ranges from 30 to 50%. The same applies to de-NOx installations, and control devices reducing the emissions of fine particles. Hence, it can be concluded that the technical measures for mercury 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 [3].

The UNEP Chemicals study [3] also concluded that efficient, non-technological measures and pre-treatment methods are available for the reduction of mercury releases from various uses of products containing mercury. These measures include a ban on the use and substitution of products containing mercury and cleaning raw materials (e.g. coal cleaning), as well as energy conservation options, such as energy taxes, consumer information, energy management and improvement of efficiency of energy production through a co-generation of electricity and heat in coal-fired power plants. Other potential measures affecting mercury emissions comprise prevention options, aimed at reducing mercury in wastes and material separation, labelling of mercury-containing products, and input taxes on the use of mercury in products [3].

For coal combustion, the incremental cost of mercury emission reduction varies substantially, depending on several 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 percentage reduction expected. Wet scrubbers installed primarily for mercury have been estimated to cost between US$168,000 and US$384,000 per kg of mercury removed [3]. On average, these estimates are very close to the cost of US$234,000 per kg mercury removed, as estimated and used in the study of the effectiveness of the UN ECE heavy metals (HM) Protocol and cost of additional measures [7].

In general, high mercury emission control efficiencies, exceeding 95%, can be obtained through a combination of FGD and electrostatic precipitators (ESPs) or fabric filters (FFs) with an "add on" type of equipment, specific for the removal of mercury 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. In 2005, the U.S. Environmental Protection Agency (EPA) had estimated that it would cost between US$149,300 and US$154,000 per kg to achieve a 90% control level using sorbent injection [8]. But, according to Sloss [9], there has been a strong decrease in the costs to achieve 90% mercury capture in recent years as a result from investments in research and development. Field test results published in 2007 showed that the cost of 90% mercury control could be lowered to less than US$10,000 per pound (22,000 per kg) mercury removed [10].

4.2. Mercury emissions within the reduction scenarios in year 2020

The efficiency of mercury removal for 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 future scenarios in the UNEP report on Global Atmospheric Mercury Assessment [1]. These emission factors are also available in the ESPREME database for individual emission source categories.

Emissions estimated for the 2020 SQ scenario can be lowered even below the 2005 emission level by applying technological and non-technological measures that will reduce emissions of mercury to the atmosphere by the year 2020. The mercury emissions in 2020, in accordance with the assumptions defined within the EXEC and MFTR scenarios, are estimated to be 1070 metric tonnes and 860 metric tonnes, respectively. Details on methodology of emission estimates are presented in the UNEP report on Global Atmospheric Mercury Assessment [1]. A comparison of mercury 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 Fig. 2.

The largest increase of mercury emissions from by-product sources in the period from 2005 until 2020 is expected in Asia, assuming that the current mercury pollution will continue until 2020 (the SQ scenario). Detailed analysis carried out within the UNEP report on Global Atmospheric Mercury Assessment indicates that the increase of Asian emissions is primarily due to the expected increase of mercury emissions in China followed by India [1].

A significant decrease in mercury emissions from by-product sources between 2005 and 2020 is estimated for all continents for the emission scenarios EXEC and MFTR assuming the implementation of efficient emission control devices. As expected, the largest emissions of mercury in 2020 are estimated for Asia. The decreases of mercury emissions in Europe, North America, Australia, Japan and Russia are expected to be between 40 and 60%.

Hence, it can be concluded that a decrease by one third of total emissions of mercury released in 2005 could be achieved by 2020, provided that the assumptions of the EXEC are met. Furthermore, as much as 50% of the 2005 total emission can be reduced by 2020, if the assumptions of the MFTR scenario are met. These decreases would be facilitated by reductions in mercury emissions resulting from changes in patterns of consumption for coal used to produce electricity and heat. There is also a clear decrease in mercury emissions estimated for various industrial sectors, such as cement production and ferrous and non-ferrous metal production.

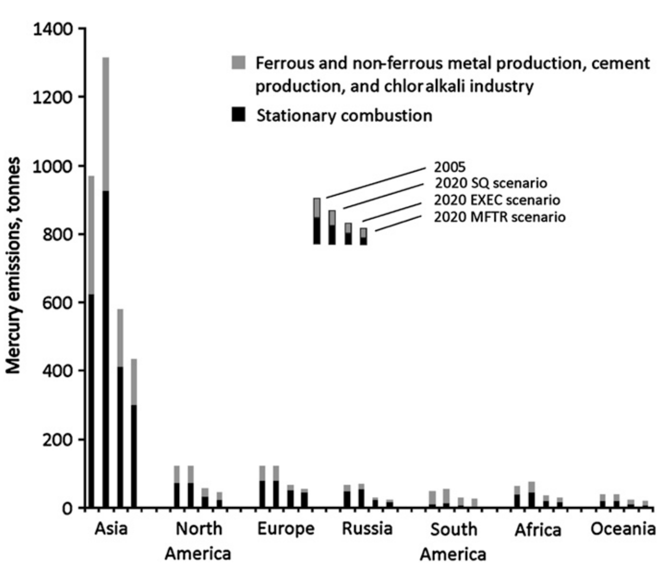

Fig. 2. Comparison of emissions of mercury as a by-product in the year 2005 with the 2020 emission scenarios for various regions worldwide. (From Pacyna et al. 2009 [5]).

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

5. Atmospheric transport, emission deposition and potential risks

Mercury has a long atmospheric residence time. Mercury emitted in industrialised regions can therefore be transported to other continents or to sensitive ecosystems in remote regions, such as the Arctic [11]. The relative importance of global versus regional sources and source–receptor relationships in the Northern Hemisphere was evaluated in Travnikov [12], who concluded that about 40% of annual mercury deposition to Europe originates from external sources, including 15% from Asia and 5% from North America. The latter is far more exposed to 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 and 14% to European sources. In contrast, the contribution of all external sources for Asia does not exceed 32%.

The UNEP assessment [1] concluded that concentrations of mercury in ambient air are generally too low to represent any risk of adverse health effects for humans. The concern over mercury 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 and transformed through the food web. Nevertheless, deposition increases of mercury above threefold have been documented near emission sources; depositions depend on stack height, the quantity and chemistry of the emitted mercury, and local atmospheric chemistry [13,14].

Bacteria in aquatic systems convert a small proportion of the deposited mercury to methyl mercury (MeHg), which once transformed through the food web bioaccumulates in fish. However, aquatic systems vary in the efficiency with which atmospherically-deposited mercury is transformed to MeHg and bioaccumulated [15]. For example, the mercury concentration of fish in adjacent lakes can vary as much as 10-fold, even when atmospheric mercury levels are comparable [16]. In a given aquatic system, the production of MeHg is believed to be approximately proportional to atmospheric mercury deposition (but with variable response time and magnitude), so it is likely that historical increases in mercury emissions have increased MeHg concentrations in fish [15].

Mercury can bioaccumulate and biomagnify in the form of MeHg in food-webs (particularly aquatic food-webs) to levels dangerous to organisms, including humans. A major assessment of the environmental effects of mercury has been carried out within AMAP [11]. It was concluded that piscivorous fish such as tuna and top predators experience the greatest exposure to MeHg. Dietary MeHg could, moreover, adversely affect reproduction in wild populations of fish in surface waters containing food-webs with high concentrations of MeHg [11].

6. 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 [11]. Various reference doses with regard to the optimum safe level of MeHg content in fish have been proposed by various organizations, such as the Food and Agriculture Organization (FAO), the European Commission, Health Canada, the U.S. Food and Drug Administration (FDA), and the US EPA, ranging from 0.1 to 0.4 μg of methyl mercury per kg of body weight per day [17].

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. Populations 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 mercury 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 [18].

MeHg is a developmental neurotoxicant at dangerously high environmental levels in many regions of the world. It can cause neurological effects, including reductions in IQ 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 case of severe exposure, there is a risk for reproductive outcomes, immune system effects and premature death [18,19].

A database of health end points has recently been compiled under the EU DROPS project (http://drops.nilu.no) [20]. Neurotoxic impacts were found to be the main human health end point for mercury. The most cited studies on neurotoxic impacts due to mercury have followed cohorts of children among three populations in New Zealand [21], the Seychelles [22], and the Faroe Islands [23], where diets 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. [24] consider several possible forms of the dose-response function (DRF) with and without threshold effect in estimating the societal cost of the IQ decrement in the USA. These DRFs were revised in Trasande et al. [25]. The revised function of DRF for mercury by Axelrad et al. [26] is based on an integrated analysis of the New Zealand, the Seychelles, and the Faroe Islands studies as well as the estimates of Trasende et al. [24]. This function is also used in the Spadaro and Rabl [27] study. The impacts are relevant for children due to the transmission of toxic substance eaten by the mother during pregnancy. Regarding the impacts among adults, no significant correlation with neurotoxic impacts was found due to the lower sensitivity of the adult brain [28]. There are other impacts due to mercury at low doses documented in the literature such as on coronary heart disease. However, a review by Virtanen et al. [29] shows that the case seems to be less clear than for neurotoxic impacts (Quoted also in Spadaro and Rabl [27]).

The slope factor (i.e. the number of IQ point losses due to daily (yearly) intake of MeHg) in the Spadaro and Rabl [27] study, is a product of the relation between intake dose of methyl mercury and concentration, maternal blood concentration, a ratio cord blood concentration, a ratio hair/cord blood, and a dose–response function for IQ loss per increase in maternal hair mercury. The result is a slope factor 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 points loss while it is 0.087 IQ points loss for zero threshold.

7. Costs of damages caused by mercury pollution

The costs referred to here are the external costs associated with measurable damages to human health and the environment. For human health, the costs of damages are related directly to the dose of MeHg received through inhalation of contaminated air and the ingestion of polluted food. The slope factor links the IQ changes with the intake of mercury-containing food during pregnancy, which might have a direct and indirect effect on future earnings. The direct effect of reduced IQ is traced through its impact on job attainment and performance. Reduced IQ may also indirectly lead to reduced educational attainment, which, in turn, affects earnings. The total cost of damages related to welfare parameters of changes in development impairment have been reviewed in the DROPS project [20]. This cost includes those related to loss of earnings, loss of education, as well as the opportunity cost while at school [30]. A literature review based on studies conducted in the USA and related to costs based on IQ decrement was performed by Rabl and Spadaro [27]. These damage costs can be listed as follows [24,31–33,34]:

- Lutter (2000) indicates 3,000 € (US$ 4500) 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 [27] concluded on the basis of this literature review that it is proper to use €12,000 (US$18,000) per IQ point. To estimate a worldwide average cost of damage per kg of mercury emitted due to ingestion, the method links statistics on country specific population and birth rates (i.e. the fraction of the population affected), to the slope factor and cost of IQ decrement (see Spadaro and Rabl [27] for more information). The US costs based on the IQ decrement is adjusted by transferring the country specific cost to other countries using the Gross Domestic Product (GDP) per capita expressed as Purchasing Power Parity (PPP) as a weighting factor. The method, called *benefit transfer*, uses the following formula:

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

C_i is a damage cost in a specific country and C_{USA} is the damage cost in the USA. Based on this formula, the costs are dependent on the GDP_{ppp} per capita level in the studied country. Thus, a country with low GDP_{ppp} will have a lower cost of IQ loss and vice versa for a country with a high GDP_{ppp}. For a dose threshold of 6.7 g/day of MeHg per person, the global average estimate was about US$1500 per kg mercury emitted. This is the value used in this paper when calculating damage costs associated with the ingestion pathway.

As a rough estimate, instead of making the benefit transfer for each country, estimates for the costs of damages resulting from inhalation are based on results from the DROPS project for inhalation of mercury polluted air [20]. To reflect the differences in technology composition, damage costs are used for two case countries, Poland and Germany. The amount of €0.8582 (US$1.2873) per kg of mercury (the case of Poland) is used for the countries in Asia (except Japan), Eastern Europe, Africa and South

America, while €1,419 (US$2.1285) per kg of mercury (the case of Germany) was used for the rest of the world. The procedure was simply to multiply the damage costs per kg of mercury to the emissions in the respective country.

The costs of damages resulting from ingestion and inhalation were estimated in the report to the Nordic Council of Ministers and revised for this paper for various continents and source categories in year 2020 at the emission levels defined in the SQ [4]. The corresponding damage costs for inhalation of mercury are estimated to be US$2.9 million (2005 dollars) in 2020. This is a small fraction of the costs from ingestion of contaminated food, but it is important to keep in mind that 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 corresponding global damage costs from ingestion of mercury are US$2.9 billion (2005 dollars) for by-product emissions and US$0.8 billion (2005 dollars) are from intentional use emissions. By far, the highest damage cost of by-product emissions is associated with emissions from coal use, while from intentional utilisation; the highest damage costs are associated with artisanal and small-scale gold mining. The results are presented in Fig. 3.

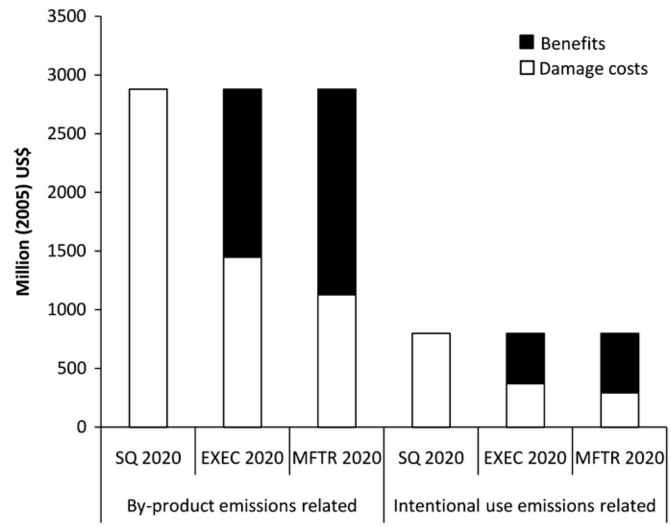

Fig. 4. Comparison of damage costs and benefits within the 2020 emission scenarios for by-product emissions and intentional use.

8. Societal benefits from reducing mercury pollution beyond the Status Quo (SQ) scenario

8.1. Monetized societal benefits

Benefits are, in this paper, estimated as the difference between the costs of damages determined for the SQ scenario on the one hand, and the EXEC and MFTR scenarios on the other hand. In this way, the societal benefits in monetary terms 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 are presented in Fig. 4.

Fig. 4 indicates that introduction of emission measures in the period between 2005 and 2020 to obtain the emission reduction targets defined in the 2020 EXEC scenario would facilitate decreased societal costs by about a factor of two. The damage cost reduction for the MFTR scenario is by a factor of 2.5. In addition to these benefits, significant co-benefits from the emission control for mercury are expected since control technologies used to reach the emission levels stipulated in the reduction scenarios are almost all multi-pollutant emission reduction technologies.

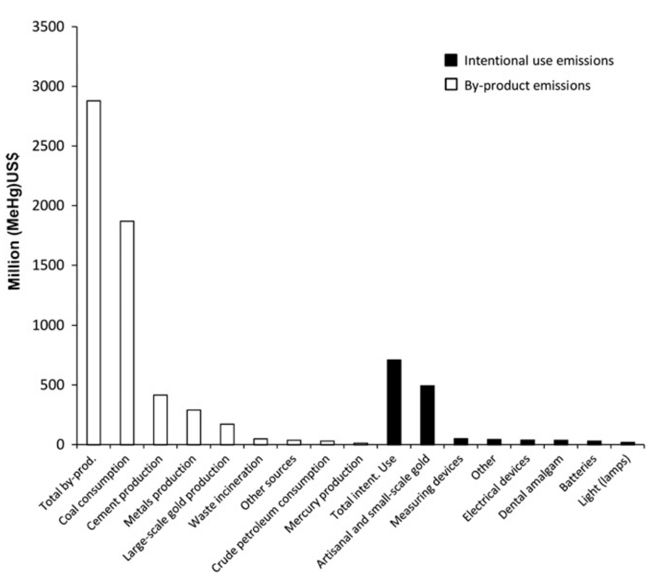

Fig. 3. Annual damage costs due to ingestion and inhalation of Hg for by-product- and intentional use source categories in year 2020, SQ scenario, (million 2005 US$).

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

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

8.2. Other monetary benefits

Only a few studies attempt to estimate human health benefits in a more complete way. A case study from 2004 (Rae and Graham [19]) comprised the South Atlantic coast from North Carolina to northern Florida. This was an area, at the time, which had 85% higher exposure levels than the US in general. It was estimated that human health benefits from avoiding non-fatal heart attacks, mortality and child hypertension were about seven times higher than if only the loss of IQ points was estimated. 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 such as premature death [19].

For the evaluation of environmental damage, very little information is available on the impacts of mercury. However, a contingent valuation study was conducted in the Eastern USA [35]. Respondents were asked about their willingness-to-pay for reducing mercury deposition in the Chesapeake Bay area. Assumptions from this study were 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 willingness-to-pay estimates for 5, 12, 21 and 35% reduction respectively (with a full effect after 20 years), indicates that households would be willing to pay about US$270 for a 50% reduction (similar to the EXEC scenario) of deposited mercury, or 16 (2005 dollars) for the year 2020 (assuming a 3% discount rate for the years 1999–2005). This implies that average willingness-to-pay for 50% reduction is US$6 (2005 dollars) per person for the EXEC scenario and US$8 (2005 dollars) 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 household size in the study was 2.6 persons. Using the Hagen et al. study-results [19], the average willingness-to-pay in the world would be US$1.4 per person for the EXEC scenario and 1.8 for the MFTR scenario. The global benefits for the environment is thus US$9.4 billion for the EXEC scenario and US$12.1 for the MFTR scenario since there are about US$6.7 billion persons in the world. The resulting values from the estimate of damage costs due to IQ-loss and when taking into account the assumptions derived in the literature, are shown in Fig. 5.

The societal benefits of reducing IQ-loss are then multiplied by 7 to meet the assumptions made from the Rea and Graham, 2004 [19] study and is referred to as other human health effects in Fig. 5. Based on the Hagen et al. [33] study for estimating the societal benefits on the environment, the total estimate for benefits from the EXEC and MFTR scenarios are US$24 and 29 billion, respectively.

From these results, it is evident that the size of the benefits of reducing mercury emissions varies greatly, and a thorough analysis of several aspects of these calculations would need to be made before apply to a quantitative cost-benefit assessment.

9. Uncertainty

Uncertainties are recognised in several stages of the assessment. First, uncertainties are attributed to the emission estimates, since they are based on a number of assumptions on emission factors, technology, consumption, production, use, as well as social and economic variables. Uncertainties to the emission estimates are assumed to be +-25–30% by source category and +- 27–50% by geographical continent. A more detailed description of these uncertainties is presented in the UNEP assessment [1]. Secondly, uncertainties are attributed to the monetized impact of IQ decrements from the mercury emissions. For a 6.7 μg/day of methyl mercury dose threshold, Spadaro and Rabl, 2008 [27] ranging the cost estimate from 126 to 2230 (1500 as the mean value) US$/Kg mercury emitted within a 68% confidence interval. A dose threshold of 5.7 μg/day of methyl mercury will lead to a range of 800–12,400 US$/Kg mercury emitted [36]. On a regional scale, Trasande et al. [25] estimated that mercury emissions from American power plants would impose damage costs due to IQ decrement, of 1.3 billion US$ (range of 0.1–6.5 billion). The U.S. EPA reported in *Regulatory Impact Analysis of the Clean Air Mercury Rule* (which now is vacated) that the benefits gained from less IQ loss from recreationally-caught fish would be valued from US$0.25–1.56 million from reduced emissions from U.S. coal-fired power plants [37]. Within the range of uncertainties, this paper presents a global damage cost range of US$0.1–40 billion (2005 dollars) for IQ decrement within the Status Quo scenario in 2020.

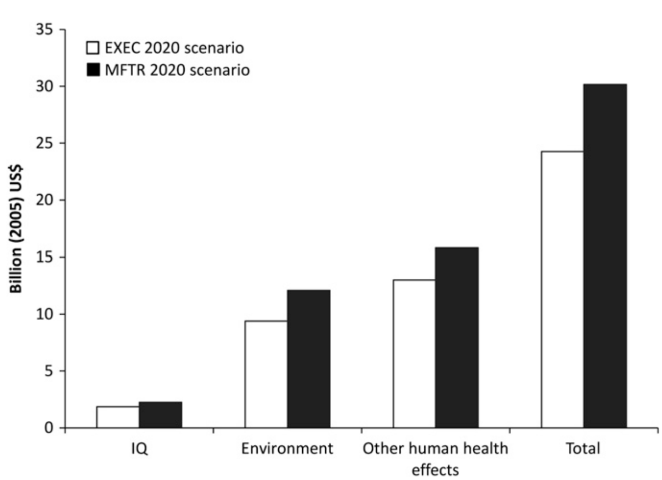

Fig. 5. Estimated total societal benefits (billion 2005 US$) (see text below for definitions).

10. Discussion and conclusions

Mercury contamination can be measured in all regions of the world due to its capacity for long range, global transport. 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 its emissions, but these assessments can only be made with information about local conditions and the degree of contamination. However, information is very scarce for many regions and a global assessment of the actual impacts is difficult to make based on the available measurement data.

Elevated risk of cardiovascular diseases (especially myocardial infarction), as well as risks for reproductive outcomes, immune system effects and premature death are all health effects that are related to severe exposure of MeHg [18,19]. In addition, there are potentially a number of environmental impacts. For a full analysis of costs and benefits, several aspects of mercury pollution, sources, impacts and co-effects need to be considered. Furthermore, it is of great importance to analyze to what extent human health effects other than IQ loss, and environmental impacts have on the 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.

Quantification of costs and benefits can be a useful tool to inform decision-makers about the main emitting sectors and the different options for emission control. Nevertheless, it is important to acknowledge that the global debate on mercury emissions to some degree may appear misleading, if costs are presented solely in economic terms without taking into account non- quantifiable (or difficult quantifiable) impacts that may be relevant for the outcome of the analysis. For instance, cultures and entire ways of life can be threatened by pollution e.g. from high levels of methyl mercury in seafood traditionally eaten by indigenous groups in the Arctic [11]. A qualitative analysis must be added to the economic analysis before action or decisions are taken.

There are potentially a number of co-benefits related to the mercury emission reduction, especially 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, as mentioned earlier in this paper. 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 known to be related to lung and cardiovascular diseases, and SO_2 induces the acidification and corrosion of buildings. A study for the European Environmental Bureau has shown that, for Europe (which has already reduced much of PM and SO_2 emissions), the benefit/cost ratio for introducing best available technologies for PM and 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 mercury emissions [38].

The Global Atmospheric Mercury Assessment, estimated that global emissions of mercury to the atmosphere will increase from about 1930 tonnes in 2005 to about 2390 tonnes in 2020, if no further action is taken to reduce mercury emissions globally (the SQ scenario) [1]. Consequently, revised estimates from the report to the Nordic Council of Ministers has shown that loss of IQ will lead to annual damage costs of US$2.9 billion for emissions from by-product sources. The corresponding estimate from intentional use of mercury is US$0.7 billion. 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. However, within the uncertainties, the cost range is likely to be US$0.1–40 billion.

As shown in the emission reduction scenarios, large benefits can potentially be achieved by introducing technical and non-technical measures for reduction of global mercury emissions. From reduced IQ loss alone, the annual damage costs can be reduced significantly leading to benefits of approximately US$1.8 billion and 2.2 billion, corresponding to the two different emission scenarios EXEC and MFTR, respectively.

The decreases of total emissions of mercury between 2005 and 2020 are mostly driven by the decreases in mercury emissions for the consumption of coal to produce electricity and heat. There is also a significant decrease in mercury emissions estimated for various industrial sectors, such as cement production and ferrous and non-ferrous metal production. The assessment in the UNEP Chemicals report [3] showed that high mercury removal efficiencies can be obtained from a combination of flue gas desulphurization (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. Non-technological measures such as ban on use and substitution of products or fuels containing mercury, as well as coal cleaning can potentially be important for future mercury emission reductions. Additionally, energy conservation options, such as energy taxes, consumer information, energy management and improvement of efficiency of energy production through co-generation of electricity and heat in coal-fired power plants can prove to be important. Scenarios for future intentional use of mercury are uncertain due to the lack of consistent international agreements and policies to reduce mercury demand. However, as a basis for sound decision-making, scientific focus should be on achieving more detailed information on alternative strategies and associated costs of reducing emissions, as well as quantitative information on source–receptor and dose–response descriptions in order to identify benefits from reducing impacts on human health and ecosystems.

Acknowledgements

A large part of the information presented in this paper has been prepared within the Nordic Council of Ministers project on socio-economic costs of continuing the Status Quo of mercury pollution. The authors of this paper are grateful for financial support for this work by the Nordic Council of Ministers. The authors would also like to acknowledge the contribution of Dr. Damian Panasiuk and Anna Glodek at NILU Polska, and also, Dr. Alice Newton at NILU for help on reviewing the paper.

References

[1] The UN Environment Programme Chemicals. Mercury Programme. Global Atmospheric Mercury Assessment: Sources, Emissions and Transport, December 2008. Available at: (http://www.chem.unep.ch/mercury/publications/default.htm).

[2] Streets DG, Zhang Q, Wu Y. Projections of global mercury emissions in 2050. Environ Sci Technol 2009;43(8):2983–8.

[3] UNEP Report on General qualitative assessment of the potential costs and benefits with each of the strategic objectives set out in Annex 1 of the report of the first meeting of the open ended working group. The UN Environmental Programme, 2008. Available at: (http://www.chem.unep.ch/mercury/OEWG2/Meeting.htm).

[4] Pacyna J.M., Sundseth K., Pacyna E.P., Munthe J., Belhaj M., Astrom S., et al. Socio-economic costs of continuing the status-quo of mercury pollution. Report to the Nordic Council of Ministers. Tema Nord 2008:580, Final Draft August 14, 2008. Final draft available at: (http://www.norden.org/pub/sk/showpub.asp?pubnr=2008:580).

[5] Pacyna, E.G., Pacyna, J.M., Sundseth, K., Munthe, J., Kindbom, K., Wilson, S., et al. Global emission of mercury to the atmosphere from anthropogenic sources in 2005 and projections to 2020. Atmospheric Environment, in press, doi:10.1016/j.atmosenv.2009.06.009.

[6] Hilson G. Abatement of mercury pollution in the small-scale gold mining industry: restructuring the policy and research agendas. Sci. Total Environ. 2006;362(1–3):1–14.

[7] Visschedijk A.J.H., Denier van der Gon H.A.C., van het Bolscher M., Zandveld, P.Y.J. Study to the effectiveness of the UN ECE heavy metals (HM) proticol and costs of additional measures. TNO report No. 2006-A-R0087/B, Apeldorn, The Netherlands; 2006.

[8] U.S. EPA. Control of mercury emissions from coal-fired electric utility boilers: an update. Air Pollution Prevention and Control Division, National Risk Management Research Laboratory. Research Triangle Park, NC: United States Environmental Protection Agency; 2005.

[9] Sloss LL. Economics of mercury control. IEA Clean Coal Centre June, 2008.

[10] Feeley, T.J. III, Brickett, L.A., O'Palko, A., Jones A.P., DOE/NETL's Mercury control technology R&D program-taking technology from concept to commercial reality, Presented at the MEGA Symposium, Baltimore, MD; August 2008.

[11] AMAP. AMAP Assessment 2002: heavy metals in the arctic. arctic monitoring and assessment programme (AMAP), Oslo, Norway; 2002.

[12] Travnikov O. Contribution of the intercontinental atmospheric transport to mercury pollution in the Northern Hemisphere. Atmos Environ 2005;39:7541–8.

[13] Lindberg SE, Bullock OR, Ebinghaus R, Engstrom DR, Feng X, Fitzgerald WF, et al. A synthesis of progress and uncertainties in attributing the sources of mercury in deposition. Ambio 2007;36:19–32.

[14] Swain EB, Jakus PM, Rice G, Lupi F, Maxson PA, Pacyna JM, et al. Socioeconomic consequences of mercury use and pollution. Ambio 2007;36(1):45–61.

[15] Munthe J, Bodaly RA, Branfireum BA, Driscoll CT, Gilmour CC, Harris R, et al. Recovery of mercury-contaminated fisheries. Ambio 2007;36:33–44.

[16] Wiener JG, Knights BC, Sandheinrich MB, Jeremiason JD, Brigham ME, Engstrom DR, et al. Mercury in soils, lakes, and fish in Voyageurs National Park (Minnesota): importance of atmospheric deposition and ecosystem factors. Environ Sci Technol 2006;40:6261–8.

[17] Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO). Joint FAO/WHO Expert Committee on Food Additives. Sixty-first meeting, Rome; 2003. Report available at FAO web pages.

[18] Mergler D, Anderson HA, Hing LMC, Mahaffey KR, Murray M, Sakamoto M, et al. Methylmercury exposure and health effects in humans: a worldwide concern. Ambio 2007;36:3–11.

[19] Rae D, Graham L. Benefits of reducing mercury in saltwater ecosystems, a case study. US EPA, Office of Wetlands, Oceans, and Watersheds; 2004.

[20] Pacyna JM. Publishable final activity report of the EU DROPS project. The EU DROPS project. Kjeller, Norway: Norwegian Institute for Air Research; 2008.

[21] Kjellstrom T, Kennedy P, Walls S, Mantell C. Physical and Mental development of children with prenatal exposure to mercury from fish. Stage I: Preliminary Tests at Age 4. Report 3080. Solna, Sweden:National Swedish Environmental Protection Board; 1986.

[22] Myers GJ, Davidson PW, Cox C, Shamlaye CF, Palumbo D, Cernichiari E, et al. Prenatal methylmercury exposure from the ocean fish consumption in the Seychelles child development study. Lancet 2003;361:1686–92.

[23] Grandjean P, Weihe P, White RF, Debes F, Araki S, Yokoyama K, et al. Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. Neurotoxicol Teratol 1997;19(6):417–28.

[24] Trasande L, Landrigan PJ, Schechter C. Public health and economic consequences of methyl mercury toxicity to the developing brain. Environ Health Perspect 2005;113(5):590–6.

[25] Trasande L, Schechter C, Haynes KA, Landrigan PJ. Applying cost analyses to drive policy that protects children. Ann NY Acad Sci 2006;1076:911–23.

[26] Axelrad DA, Bellinger DC, Ryan LM, Woodruff TJ. Dose–response relationship of prenatal mercury exposure and IQ: an integrative analysis of epidemiologic data. Environ Health Perspect 2007;115(4):609–15.

[27] Spadaro VJ, Rabl A. Global health impacts and costs due to mercury emissions. Risk Analysis 2008;28(No. 3). doi:10.1111/j.1539–6924.2008.01041.x.

[28] Weil M, Bressler J, Parsons P, Bolla K, Glass T, Schwartz B. Blood mercury levels and neurobehavioral function. JAMA 2005;293(15):1875–82.

[29] Virtanen JK, Rissanen TH, Voutilainen S, Tuomainen T-P. Mercury as a risk factor for cardiovascular diseases. J Nutr Biochem 2007;18:75–85.

[30] Scasny M, Maca V, Melichar J. Data set of values for benefit valuation and costs-of-illness related to relevant health impacts. The EU DROPS project. Deliverable No. D2.2. Kjeller, Norway: Norwegian Institute for Air Research; 2008.

[31] Lutter R. Getting the lead out cheaply: a review of EPA's proposed residential lead hazards standards. Environ Sci Policy 2000;4:13–23.

[32] Grosse SD, Matte TD, Schwartz J, Jackson R. Economic gains resulting from the reduction in children's exposure to lead in the United States. Environ Health Perspect 2002;110(6):563–9.
[33] Muir T, Zegarac M. Societal costs of exposure to toxic substances: economic and health costs of four case studies that are candidates for environmental causation. December. Environ Health Perspect 2001;109(Suppl. 6):885–903.
[34] Rice G, Hammitt JK. Economic valuation of human health benefits of controlling mercury emissions from US coal-fired power plants. Boston, MA: Northeast States for Coordinated Air Use Management (NESCAUM); February 2005.
[35] Hagen DA, Vincent JW, Welle PG. Economic Benefits of Reducing Mercury Deposition in Minnesota. Minnesota Pollution Control Agency and the Legislative Commission on Minnesota Resources; 1999.
[36] Spadaro, V.J., Rabl, A. Global Health Impacts and Costs due to Mercury Emissions. ARMINES/Ecole des Mines de Paris, 60 boul. St.-Michel, F-75272 Paris.
[37] U.S. EPA. Regulatory Impact Analysis of the Clean Air Mercury Rule. Final Report. United States Environmental Protection Agency. Research Triangle Park, NC, 2005. Available on: http://www.epa.gov/ttn/atw/utility/ria_final.pdf.
[38] Barrett M., Holland M. Costs and health benefits of reducing emissions from power stations in Europe. Courtesy of European Environmental Bureau. Originally published April, 2008. Available at: http://www.environmental-expert.com/resultEachArticle.aspx?cid=21293&codi=37860.