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Young Scientists Summer Program

Future mercury control strategies and associated costs

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Approved by:

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This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP supervisor.

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Supervisor signature:

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Abstract

Global primary mercury (Hg) emissions are caused by industrial high-temperature processes such as fossil fuel burning and metal smelting and processing, as well as Hg-added production processes and their wastes. As they enter a geochemical cycle of deposition, re-emission and bioaccumulation in aquatic food chains, more communities than ever are at risk of Hg poisoning. This grave pollution issue has given rise to the first global health and the environment agreement in almost a decade - the Minamata Convention on Mercury. As Hg emissions are being regulated more explicitly and strictly within the framework of the Minamata Convention, Hg-specific end-of-pipe air pollution control devices (APCDs) as well as other regulatory measures for Hg reduction have seen a boost in research..APCDs for ‘traditional’ pollutants, e.g. for SO_2, NOx and particulate matter (PM), often reduce Hg emissions in thermal power stations and other Hg-emitting industries like incinerators and cement production as a co-benefit, but this effect is highly specific to a plant’s operating conditions, and often lead to Hg emissions being redirected into other solid or aqueous waste streams..

Future Hg control strategies will also depend on possible changes in the main emission sources due to clean air and climate policy. While the decarbonization of the power sector may lower Hg emissions, increased mining of non-ferrous metals necessary for the renewable energy transition is also associated with Hg emissions. Both may influence the magnitude of future along with prevalent emission sources and (cost-)optimal control solutions of the relevant sources.

This report reviews the current control technologies for Hg across all sectors, updating the GAINS database to Hg-specific control technologies, as well as extending the co-benefit calculations, which calculate the impact of PM and SO_2 control on Hg abatement efficiencies. It presents a preliminary dataset of associated Hg abatement costs, as well as a review of current and likely future control strategies, laying the groundwork for in-depth projections of Hg emissions over the upcoming 30 years. The data collection focuses on the EU and China, but aims at a global implementation of Hg-GAINS at a later stage.

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List of Abbreviations

AC	…	Activated carbon
APCD	...	Air pollution control device
AP	...	Acid plant
ASGM	...	Artisanal and small-scale gold mining
BAT	...	Best available technique
BEP	...	Best environmental practice
BNP	...	Boliden Norzinc Process
CCS	…	Carbon Capture & Storage
CFPP	...	Coal-fired power plants
CYC	...	Cyclone
ESP	...	Electrostatic precipitator
FF	...	Fabric or baghouse filter
FGD	...	Flue gas desulfurization
GAINS	…	Greenhous Gas - Air Pollution Interactions and Synergies model
GHIND	...	Good housekeeping
GP	...	Good Practice
Hg	...	Mercury
HED	...	High-efficiency deduster
LHGCO	...	Low-mercury coal
NFME	…	Non-ferrous metals
SINJ	…	Sorbent injection
SPC	...	Stationary sorbent modules
WFGD	...	Wet flue gas desulfurization
WSCRB	...	Wet scrubber

Introduction

The Minamata Convention on Mercury has been officially ratified in 2017, requiring its signing parties to reduce mercury emissions from a variety of sectors through a mix of product phase-out, phase-out of Hg-intensive industrial processes, sound Hg waste management, and best available technologies for Hg emission control from the power sector and other combustion related to industrial activities and metal smelting (UNEP, 2013). While phase-out dates for products have already been set, the BAT/BEP guidelines for different industries allow room for interpretation within the National Action Plans of the signing parties, and offer a wider range of technological control options (e.g. Lin et al., 2017). A number of publications have reviewed technologies for the coal-fired power sector (Pacyna et al., 2016; Giang et al., 2015; Wu et al., 2018a) and some production (non-ferrous metal production, cement production) and waste incineration (Wu et al. 2018a). Several studies have looked at the geographical distribution of Hg pollution, as well as Hg health benefits. Hg-GAINS, as developed by Rafaj et al. (2013) (see also Amann et al., 2011) is the only model which currently represents *all* anthropogenic emission sources on a sector-by-sector basis, but currently, only co-benefit technologies are implemented into it for the combustion and production sectors. Through this work, we take Hg-GAINS into the Minamata era of active mercury emission abatement. We review the available Hg control options across all emission sources, adding novel and Hg-specific abatement techniques for a better representation of detailed emission scenarios. As a first step towards a model in which the costs of different policy control options can be assessed, we collect and structure cost data for the Hg-specific control dataset. For both abatement technology and cost data, we expand the co-benefit principle, by which the benefits of traditional air pollution control for particulate matter and SO_2 to Hg reduction are computed.

Background

It has now been known for two decades (UNEP, 2002) that atmospheric mercury (Hg) emissions are the root cause of a pollution problem that is projected to cost $19 trillion (2020 US dollars) for accumulated health effects for Hg exposure between 2010 and 2050 (Zhang et al., 2021). It is designated one of the top ten chemicals or groups of chemicals of major public health concern by the WHO. Due to the long-range transport of elemental Hg in the atmosphere, the pollutant is distributed globally (e.g. Selin, 2009; AMAP/UNEP, 2013). Due to the metal's unique volatility and (redox-)reactivity at ambient conditions, frequent species changes can cause the deposition and re-emission of legacy emissions, as well as bioaccumulation of the most toxic Hg species, methyl mercury, in the aquatic food chain, which is a grave health issue for communities and individuals which rely on a diet of high fish or marine mammal intake (UNEP, 2019; p. 56). While geogenic Hg emissions to the atmosphere also exist, e.g. from volcanic eruption, anthropogenic emissions have increased the Hg content in the atmosphere by 450% above natural levels (AMAP/UNEP, 2019) and the time for mercury to return to a permanent sink such as deep ocean sediements is estimated to be up to 3000 years (Selin, 2009), demonstrating that global cooperation and foresightful policy are essential to tackle this pollution issue.

To break this cycle of emissions, re-emissions and magnifying pollution, the Minamata Convention on Mercury was adopted in 2013, has entered into force in 2017 and is presently ratified by 134 countries (UNEP, 2013). The first international health and environment treaty on hazardous substances in almost a decade, it recognises that Hg emissions urgently have to be tackled at the global level. It aims to reduce releases "mercury and mercury compounds" by targeting them at different levels of the release cycle, such as trade, use in production, use in products, emission sources, and wastes. The issues are on one hand addressed by technical solutions, such as BAT/BEP recommendations for Hg handling, industrial emissions or waste storage, on the other hand require political and regulatory action, such as bans on mercury trade, specific products, and artisanal gold mining, demonstrating a “life-cycle approach” to limiting Hg emissions (e.g. Selin, 2014; Giang et al., 2015).

Despite these efforts, global anthropogenic emissions of Hg were estimated to have risen by 20% by 2015, compared to “pre-Minamata” 2010 levels. Small emission decreases in North America and the EU were offset by a mix of increased economic activity, as well as the production, use and disposal of mercury-containing products (AMAP/UNEP, 2019; Pacyna et al,. 2016).

Several publications have calculated projections on future Hg emissions at varying scales, based on a host of different scenarios and utilising different models. A common focus of such studies is the power sector, as coal and biomass combustion for energy make up 24% of global annual Hg emissions (UNEP, 2019) - see Table 1 for the overview.

Table 11: Studies which produce projections of future Hg emissions

Model used	Scope	Addressed emission sources	Timeframe	Reference
Calculations based on emission database, scenario assumptions from eU mERCYMS project (not found online), extrapolation of EMEP emission trends.	EU	Power sector, production sector, waste incineration, “others”		Pacyna et al. (2006)
GEOS-CHEM	China, India	Coal-fired power sector	2050	Giang et al. (2015)
Calculations based on “BAT adoption model”, Energy scenarios and control technology scenarios	China	Coal-fired power sector	2030	Ancora et al. (2016)
Emission estimates based on current and future activity data (loosely based on GAINS/RAINS?) + global transport models GLEMOS and ECHMERIT[1]	global	All industrial sectors	2010 - 2035	Pacyna et al. (2016)
Emission Estimates + pollution control measures + scenario development	China	Coal-fired power stations, industrial boilers, non-ferrous metal production, cement production, gold mining, waste incineration	2015-2030	Wu et. Al (2018a)
GEOS-CHem, biogeochemical box model, Lake Hg model	Global	All, including legacy emissions, based on	2050	Angot et al. (2018)

[1] *“To estimate the various country-specific industrial goods consumption and production data in the future, a methodology consisting of a year 2035 forecast was developed based on a simple regression model that relates industrial production to a nation’s gross domestic product (GDP) per capita (representing the per capita market value of all goods and services produced within a country). The model fitted a straight line through the set of points for all countries, with the resulting slope representing the correlation between national GDP per capita PPP (purchasing power parity) and national annual production of industrial goods. The future projection was then estimated on the basis of forecasting industrial production on the expectations of development of GDP per capita PPP in various countries, based on the OECD database on previous and current GDP per capita PPP as well as the IMF future expectations on GDP per capita PPP. (Pacyna et al., 2016)*

		inventories		
EDGARv4tox2 inventory + China Regional Energy Model (C-REM) + GEOS-chem	China	All sectors	2012-2030	Mulvaney et al. (2020)

The GAINS modeling framework is uniquely suited to model anthropogenic mercury emissions from a wide range of emission sources. Originally built to inform policy questions regarding acid rain and PM, it was applied in the database has been extended to Hg in 2013, (Rafaj et al., 2013, 2014). As Hg emissions depend strongly on energy projections, the world energy outlook scenarios from the IEA, which are implemented in GAINS, offer a good “boundary/constraint” to Hg emissions. Multi-pollutant control strategies based on application rates of different APCDs, Hg-specific as well as other pollutant-specific, can be combined to good detail in order to project applications. GAINS is also multi-sectoral, making it possible to represent all relevant anthropogenic emission sources with sector-specific pollution control options (Amann et al., 2011; Rafaj et al. 2013, 2014).

Focus region China

The scientific community has paid significant attention to Hg emissions from coal power in China, which alone accounts for a quarter of Hg emissions from coal power . Increasing air quality has had a high priority over the last decade in China, and the 2013-2017 Action Plan on Air Pollution Prevention and Control has seen significant reductions in SO_2 and PM2.5 emissions (Ancora et al., 2016), as well as demonstrated Hg reduction and an improvement in health, as shown by Li et al. (2020). Since 2015, a Hg emission limit of 30 ug/Nm^3 is also in place for new and existing CFPPs and the 12th Five-Year Plan for National Environmental Protection (2011-2015) also includes an emission reduction target of 15%, compared to 2007 levels (Ancora et al., 2016). Lin et al. (2017) provide a qualitative review of the Chinese perspective and progress on Minamata.

Using the China Mercury Risk-Source-Tracking Model (CMSTM), Li et al. (2020) created an extensive plant-level inventory of Hg emissions by coal-fired power stations, installed traditional pollution control options, and their effect on Hg emissions, paying attention to several groups of measures: (1) closure of small and ineffective power stations, (2) retrofitting of APCDs, (3) efficiency improvements and coal washing. Giang et al. (2015) developed different scenarios for future of Hg emissions from the coal-fired power sector under different assumption of how the Minamata protocol would be implemented, constructing scenarios based on a mix of policy review and expert interviews; Their study focussed on emissions from coal-fired power generation in China, India and the US, coupling speciated emissions estimations for a “No Additional Control” scenario, a “Minamata Flexible” scenario and a “Minamata Strict” scenario to the global Hg transport model GEOS-Chem, considering a set of 10 different control strategies, including one exclusively for Hg control. Mulvaney et al. (2020) produce projections until 2030, assessing the co-benefits of climate policy on Hg emissions in China in 11 economic sectors of the EDGAR database by looking at different climate policy and Minamata scenarios. Wu et al. (2018a,b) provide the most comprehensive technological control strategies for the CFPP, industrial boilers, non-ferrous metal smelting, cement production and waste incineration sector, projecting emissions until 2030 under different Minamata scenarios.

Aims & Objectives

The aim of this project is to bring Hg-GAINS into the "Minamata Era" by updating the technologies to represent recent developments, as well as drafting policy scenarios that capture the most recent Minamata convention targets, as well as capturing the impact of climate policy and air pollution policy on future mercury emissions. Adding the cost of Hg-specific technologies aims to set the model apart with a unique functionality that will benefit policymakers, and enable comparisons between the cost and the gain of conforming with the treaty.

Methodology

Update of Hg-specific emission control options

Review of Hg control options & aggregation into GAINS categories

Recent academic literature, government reports and the Minamata Convention on Mercury were reviewed to produce a list of currently applied Hg control technologies, as well as future recent technological developments. These are technologies which are commercially developed and available at scale in at least one emission sector, but might not be widely applied at scale yet. They can be expected to contribute as control options when tighter emission limits will come into force. The technologies were reviewed for their applicability and efficiency in different sectors and associated with different fuels, and a each combination of activity, sector and technology in GAINS was associated with a corresponding speciated removal efficiency, as well as speciated Hg emissions after control. In some sectors, "technologies" may not be technical in a strict sense, but might comprise actions such as bans of a certain process, or good housekeeping. Control technologies were reviewed and considered all sectors which Rafaj et al. (2013) attributed Hg emission factors to. Particular attention was paid to sectors where Hg-specific pollution control can reasonably expected, based on literature sources. Table 2 provides an overview of all sectors. Where sector sub-categories or names are used in this report, the descriptions are provided in the text. A detailed description of sub-sectors also relevant for this study can be found in the supplement of Klimont et al. (2017), table S8.1

Table 2: Emission sources considered in this report, based on emissoin sources associated with Hg emission factors in GAINS (Rafaj et al., 2013)

Emission source	Abbreviation	Short description
Gold mining	AU	Large scale and small scale gold mining
Conversion	CON	Emissions due to internal energy needs of energy and production sectors
Industrial	IN	Industrial boilers and other chemical processes
Mining	MINE	Coal mining
Non-energy	NONEN	No-energy Hg emissions
Other Hg	OTHER	Other Hg emissions

Power plants	PP	Power plants
Production sector	PR	Production sector, including cement production, coking, metal smelting and processing etc.
Residential	RES	No Hg-specific control technology expected
Storage and handling	STH	No Hg-specific control technology expected
Transport	TRA	No Hg-specific control technology expected
Domestic combustion	DOM	No Hg-specific control technology expected
Agriculture	AGR	No Hg-specific control technology expected

Implementation of Co-benefits: Extension of GAINS 3 capabilities

Gaseous mercury (Hg) emisisons are also abated to varying extents by particulate matter (PM), nitrous oxides (NOx) and sulfur dioxide (SO_2) control in many emission sources, most notably in the power sector, and in industrial boilers, but to some extent in all sectors where high temperatures are applied to Hg-containing substances, such as in the production industry (e.g. Wu et al., 2018a, b; Dehoust et al., 2021a). These emission abatement co-benefits were applied following the approach introduced in Rafaj et al. (2013): Based on a given emission scenario in a given year, overlaps between different emission technologies were calculated. Where relevant dust control was present, the Hg-specific emission factor for this type of dust control was applied. Similarly, in a scenario where PM control and SO_2 control are present, a Hg-specific emission factor for the specific combination of PM and SO_2 control is applied, calculated as the minimum of the application rate x of the specific PM and SO_2 control technology (see Figure 1). The overlap capabilities of the model were extended for GAINS 4, taking into account a larger variety of possible combinations, based on improved data availability. A full list of co-benefit techniques can be found in the following section “Control technologies acorss sectors”. Co-benefits for NOx were not implemented, as NOx control, when combined with particulate matter and SO_2 control, only brings Hg removal efficiency improvements of few percent, which is well within on standard deviation for all techniques studied (see e.g. Li et al., 2020; Niksa Energy Associates LLC, 2011).

The co-benefit concept was also extended to hybrid technologies which combine a Hg-specific component and PM/SO_2 control techniques. Firstly, sorbent injection is a technology whereby activated carbon is sprayed into the flue gas, efficiently capturing all species of Hg there. The overall efficacy of the technology in turn depends on the present dust control, which is calculated based on the co-benefit principle again.
Secondly, technologies which lower the Hg content in flue gas, such as coal washing, chemical modification or benefication, benefit from PM/SO_2 control devices downstream, also necessitating a co-benefit approach.

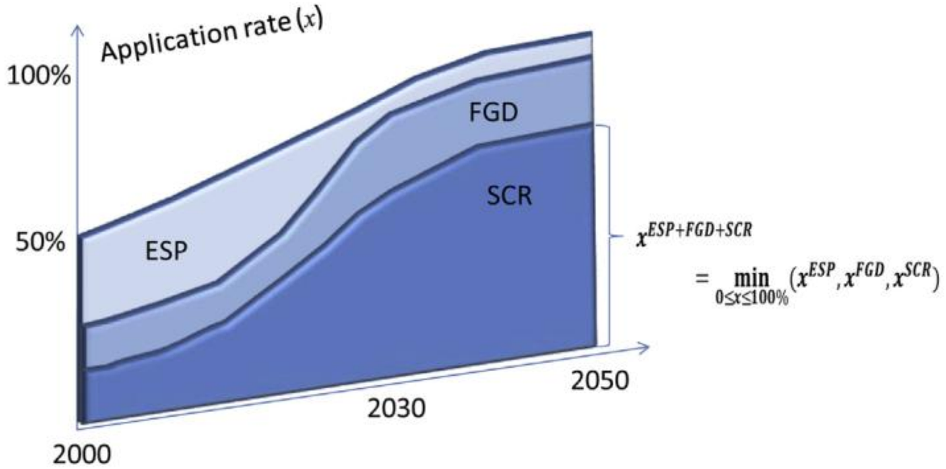

Figure 1: Source: Rafaj et al. (2013): Multi-pollutant technology approach for Hg-control in GAINS3. ESP, FGD and SCR are examples of devices to control emissions of particulates, sulfur and nitrogen oxides. ESP... electrostatic precipitator for PM control; FGD ... flue gas desulphurization for SO_2 control; SCR... selective catalytic reduction for NOx control.

Cost of pollution control options & cost co-benefits

Cost co-benefits are planned to be implemented in the same way as emission co-benefits, where only costs attributed specifically to Hg should be accounted for in the Hg module, while costs attributed to PM/SO_2 control will not, counting as a “co-benefit”.

Cost data on Hg pollution abatement has been collected by the US-EPA as preparation of the MATS regulation (Mercury air and toxics standards)s have been subject to scrutiny and amendments, due to a perceived underestimation of the costs and overestimation of the benefits of this legislation (US-EPA, 2020). Other collection of cost data include the EU-ESPREME project, were some, but not all data has been published, and the data sources are not available to the public (e.g. Pacyna et al. (2010), Pye et al., 2006). ESPREME cost estimates are reported with an accuracy of ±50%, illustrating the high uncertainty attached to them. The German Environmental Agency has recently published another report that includes cost estimates for Hg-specific control technologies, which are partially novel and for which no cost data was available (Dehoust et al., 2021a). Data concerning the Chinese market is only available from Ancora et al. (2016), who constructed cost curves based on different control strategy scenarios. This data is listed in the appendix, but has yet to be harmonized.

Control technologies across sectors

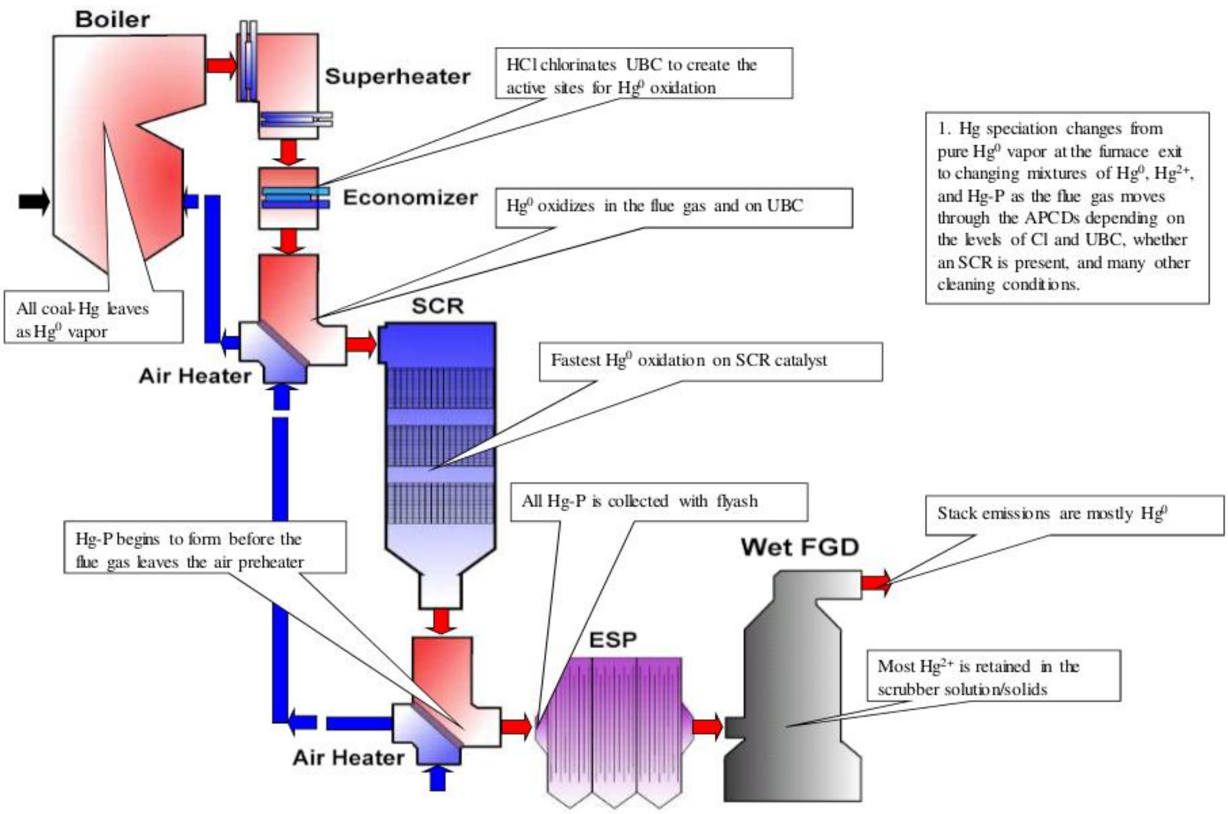

Figure 2: Mercury species transformations in the flue gas; from Niksa and Fujiwara, (2009), reprinted from Srivastava (2010).

It is important to note right at the beginning that good data on Hg-specific pollution control devices is hard to come by, and varies highly; especially outside the power sector. In many cases, data is scarce, consists of single datapoints, or is based on lab, rather than pilot-scale or full-scale feasibility tests. The most comprehensive and representative data comes from the US-EPA, e.g.from Srivastava et al. (2006) and Srivastava (2010) who evaluate full-scale and pilot-scale data at a number of U.S. Li et al. (2020) take a different, albeit unspeciated approach, reviewing Hg emission reduction data from a bottom-up power plant inventory approach. Chinese data on individual installations, as well as weighted means produced by robust methodology can be found e.g. in Wu et al. (2018a), Zhang et al. (2015) and others. Model output from the iPOG model[2] was also considered (Niksa Energy Associates LLC, 2011). In iPOG, the coal characteristics were modified to represent German and Chinese characteristics, as used in the GAINS current legislation scenario (see Table 2) of hard coal and brown coal before the model was run in all configurations and speciated emission abatement as well as emission values were recorded. This section is divided into three categories: 1. fuel modifications to achieve lower Hg emissions, 2. Hg emission reduction co-benefits derived from traditional APCDs and 3. dedicated Hg abatement technologies, which may or may not be combined with APCDs.

[2] https://web.unep.org/globalmercurypartnership/interactive-process-optimization-guidance-ipog%E2%84%A2

Table 3: Characteristics of different coal types used in large (>50 MW) coal-fired power stations in Germany and China as used in the GAINS model.

Coal	Country	Calorific value [GJ/t]	S content [%]
HC1	Germany	27.7	1
HC2	Germany	27.7	1
HC3	Germany	27.7	1
BC1	Germany	19.2	1.193
BC2	Germany	8.4	0.32
HC1	China	29	0.5
HC2	China	20.7	0.874
HC3	China	20.7	1.281
BC1	China	15	1
BC2	China	10	3

Fuel modifications

Different treatments of coal have been applied in different geographic regions of the world, to lower the sulfur and mercury content of coal. These are aggregated into the “LHGCO” category. Individual measures include coal washing, benefication, blending (e.g. Pacyna et al., 2010).

1. Coal washing may reduce the total Hg content of the coal by removing incombustible minerals, but ranges of Hg reduction from coal washing vary widely (0-64%) and are highly dependent on the coal quality in question (Jozewicz, 2010).
2. Coal upgrading or “refined coal” is becoming wide-spread in the US, where tax benefits can be claimed by coal users when a target of 40% Hg emissions reduction is reached. Hg is generally not removed from the coal, but commercial additives are mixed with it that promote the oxidation of Hg^0 to Hg^{2+} after combustion, increasing the share of Hg captured in particle filters and flue gas desulfuration scrubber solutions (Jozewicz, 2010; Dehoust et al., 2021a)
3. Similarly to coal refining, halogens such as bromine and chlorine may be sprayed onto regular coal right before coal combustion, rather than before the coal sale. Bromine and chlorine addition to coal doesn’t remove any Hg, but demonstrably lead to higher rates of oxidized Hg in the flue gas, which has a large effect on the removal efficiency of ESP and especially FGD co-benefits, which preferably retain Hg^{II}, but have low removal efficiencies for Hg^0 (Jozewicz, 2010).

Figure 3 displays literature values of the efficiency of LHGCO technologies, including their combination with different PM and SO_2 APCDs.

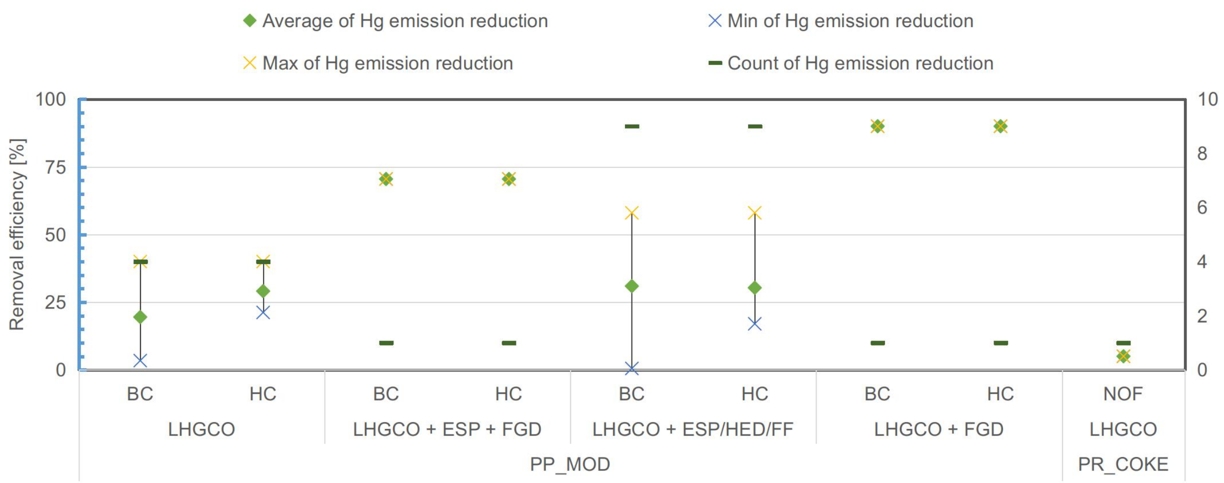

Figure 3: All literature values on Low-Hg coal techniques, and its co-benefits with PM/SO_2 control. PP_MOD ... modern power station; PR_COKE ... coking plant.

Table 4: List of separate technologies aggregated into the LHGCO category in GAINS..

Abbreviation	Description of technology	Sector	Reported by
RC	Refined coal	all coal	Dehoust et al. (2021b; p.71 ff)
BC	Beneficiated coal	all coal	Dehoust et al., (2021b; p.71 ff), Jozewicz (2010); Niksa Energy Associates LLC (2011)
WC	Washed coal	all coal	Dehoust et al., (2021b; p.71 ff), Jozewic (2010); Niksa Energy Associates LLC (2011)
FS	Coal float/sink process	all coal	Jozewicz (2010); Niksa Energy Associates LLC, (2011)

End-of-pipe Hg control in flue gas

End-of-pipe options for flue gas Hg control options are highly dependent on the chemical conditions inside an individual industrial facility, such as temperature, presence of other chemical substances such as ash, halogens, sulfur, water vapor, as well as APCDs for particulate matter, SO_2 and NOx control. While there is sufficient data for at least coal-fired power stations, and data quality for cement, waste and non-ferrous metal production industries are gradually improving, as evidenced by newly available data, mainly from China, from recent publications cited in this report (e.g. Li et al., 2020), any average may differ vastly from an individual installation. Similarly, the Hg emission levels may vary between different power plants. Data was collected from primary literature datapoints, industrial reports, aggregated reports, mean values used in other models, as well as as well as data generated from the "Interactive Process Optimization Guidance" (iPOG^{TM}) tool, which estimates mercury emissions from full-scale gas cleaning systems of coal-fired power stations Niksa Energy Associates LLC, 2011. Most sources do not provide speciated emission reduction estimates, so the ranges of mean unspeciated removal efficiencies were recored, and are displayed throughout this report.

Particulate matter control techniques

Cyclones (CYC) and different types of wet scrubbers (WSCRB) are generally only effective against removing particulate mercury (e.g. Dehoust et al., 2021b). While both methods are included in the control strategies for Chinese power stations, they are both being phased out, replaced by more efficient technologies, reflected in the current legislation scenarios in GAINS (e.g. Klimont et al. , 2017). There is limited relevant literature despite wider application in the production sector, generally assuming removal efficiencies for cyclones below 15% for smelting, other production and basic oxygen furnaces, but reporting a wide range of efficiencies for hard coal-fired power plants for wet scrubbers.

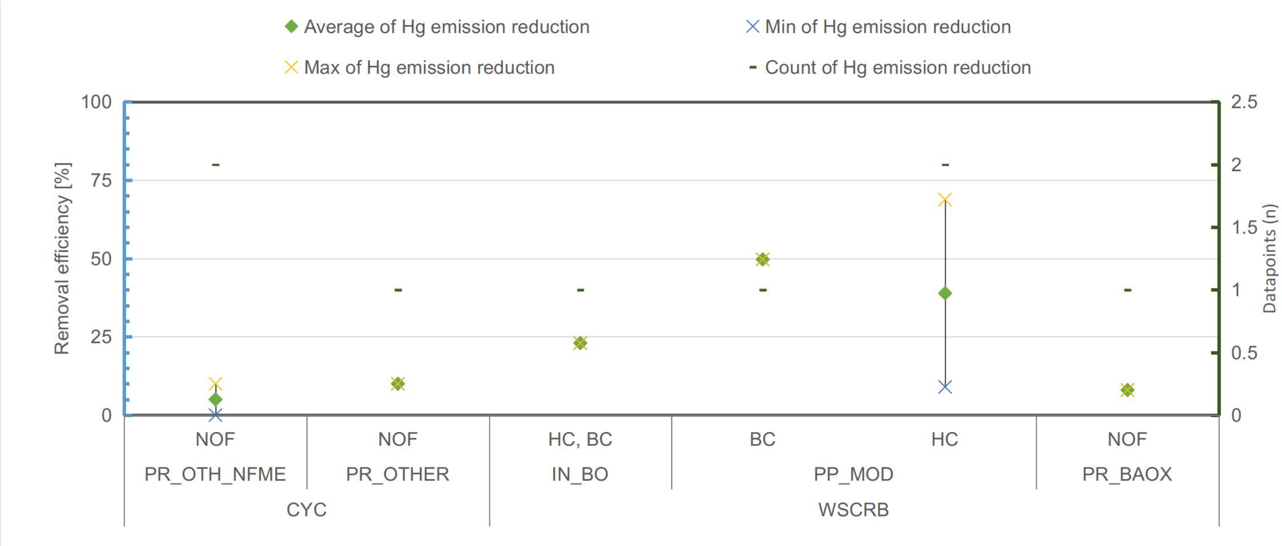

Figure 4: Literature data on cyclone (CYC) and wet scrubber (WSCRB) application in different sectors. PR_OTH_NFME ... Non-ferrous metal production. PR_OTHER ... other production, including PVC; IN_BO ... industrial boilers; PP_MOD ... modern coal-fired power stations, PR_BAOX ... basic oxygen furnace.

Electrostatic precpitators (ESP), high-efficiency dedusters (HED) and fabric or baghouse filters (FF) are common APCDs in CFPPs, industrial boilers as well as production facilities and smelters. Designed to collect particles through electrostatic precipitation (ESPs) or through physical filtering in a baghouse (FF), or a combination of both (HED), their interaction with mercury depends heavily on speciation. While all three options filter Hg^p and, to some extent, Hg^{II}, only FF have significant retention of Hg^0, as fly ash and unburnt carbon buildup on the inside of the filter bags can act as an additional sorption layer which also binds Hg^0. However, the overall efficiency of filter control differs depending on the subsequent treatment of the collected fly ash. Generally, in power generation and waste incineration, ashes are either disposed of in landfills (ideally, in line with the Basel protocol, this would be a hazardous landfill (e.g. Chalkidis et al., 2020)), or are re-used in cement kilns. For many production processes that need high temperatures, for example, in steel making, smelting and cement production, such ashes are often re-used as fuel, through which virtually all Hg is re-mobilised. This severely diminishes the co-benefit of ESP, HED or FF for Hg removal. While some sources, e.g. Dehoust et al. (2021a), assume no co-benefit of ESP, HED or FF in the sectors where as is re-used, others report significant removal, e.g. Wu et al. (2018a) and Pacyna et al. (2010) . In Figure 13, this spread becomes visible, especially for “PR” sectors. For PR_CAST and PR_CEM, values between 5% and 100% removal efficiency are reported.

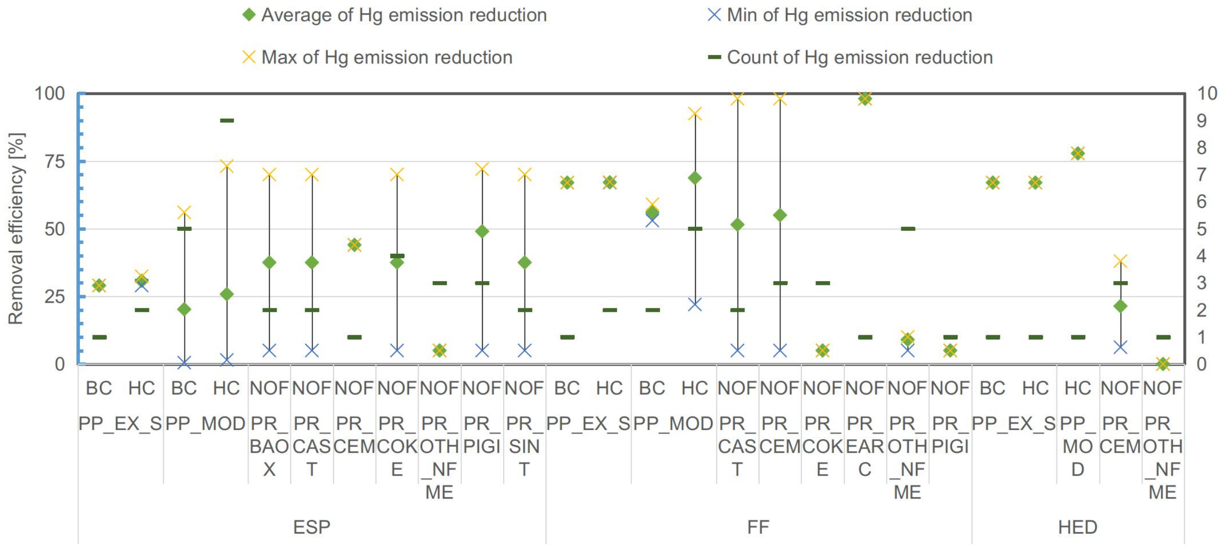

Figure 5: Particulate matter control efficiencies in different sectors. PP_EX_S ... coal power plant <50 MW, PP_MOD ... modern PP, PR_BAOX ... basic oxygen furnaces, PR_CAST ... cast iron production, PR_CEM ... cement production, PR_COKE... coking plants, PR_EARC, electric arc furnace, PR_OTH_NFME ... non-ferrous metal production, PR_PIP ... pig iron production, PR_SINT ... sintering plant.

Table 5: Aggregation of PM control technologies into GAINS techologies took into account both the similarity of technology, as well as similar effect on Hg reduction.

Technology	**Description**	**Sector**	**Reported by**	**Aggregated into GAINS category:**
DC	Dust collector	PR_NFME	Wu et al. (2018a)	CYC
ESPc	Cold ESP	PP, PR, IN, CON	Giang et al. (2015)	ESP
ESPh	Hot ESP	PP, PR, IN, CON	Giang et al. (2015)	ESP
ESD	Electrostatic demister	PR_NFME	Wu et al. (2018a) L Liang et al. (2020)	ESP
DC+FGS	Dust collector + flue gas scrubber	PR_NFME	Wu et al. (2018a)	HED
ESP/FF	High-efficiency deduster	PP, PR, IN, CON	Li et al. (2020)	HED
WET	Wet scrubber	IN_BO	Wu et al. (2018a)	WSCRB
FGS	Flue gas scrubber	PP, PR, IN, CON	Dehoust et al. (2021a, p. 170)	WSCRB
IDDRD	Integrative device for dust removal	PP	Wu et al. (2018a)	WSCRB
PS	Particle scrubber	all	Pacyna et al. (2010)	WSCRB
VS	Venturi scrubber	all	Dehoust et al. (2021a, p. 170)	WSCRB

Desulfurization techniques

Wet or dry flue gas desulfurization (WFGD) is common in large CFPPs, as well as in many production industries, and smelting of sulfidic ores. Oxidized Hg generally becomes fully dissolved in the WFGD slurry.

However, depending on the pH, temperature and other dissolved chemicals used, it may be subject to re-emission from WFGD.

In the smelting sector, sulfidic ores such as copper, lead and zinc ores often are attached to a sulfuric acid plant, making use of the smelting byproduct. Without further flue gas treatment or dedicated Hg removal, approximately 50%[3] of flue gas Hg end up in the sulfuric acid product. As this product has commercial value and its use in the fertilizer or other industries requires low levels of Hg [pers. Comm. Ole Petzold], there are several commercial Hg-specific pollution control techniques in place, discussed in the next section (Takaoka et al., 2016).

In the power sector, SO_2 control is amost always combined with PM control. This combination significantly enhances Hg co-benefits, with ample data available (Figure 75). In production, FGD is more commonly applied on its own, with the only reported ESP+FGD co-benefits reported for the coke and cement production sectors from estimates in Pacyna et al. (2010) and one HED+FGD average reported from Wu et al. (2018a).

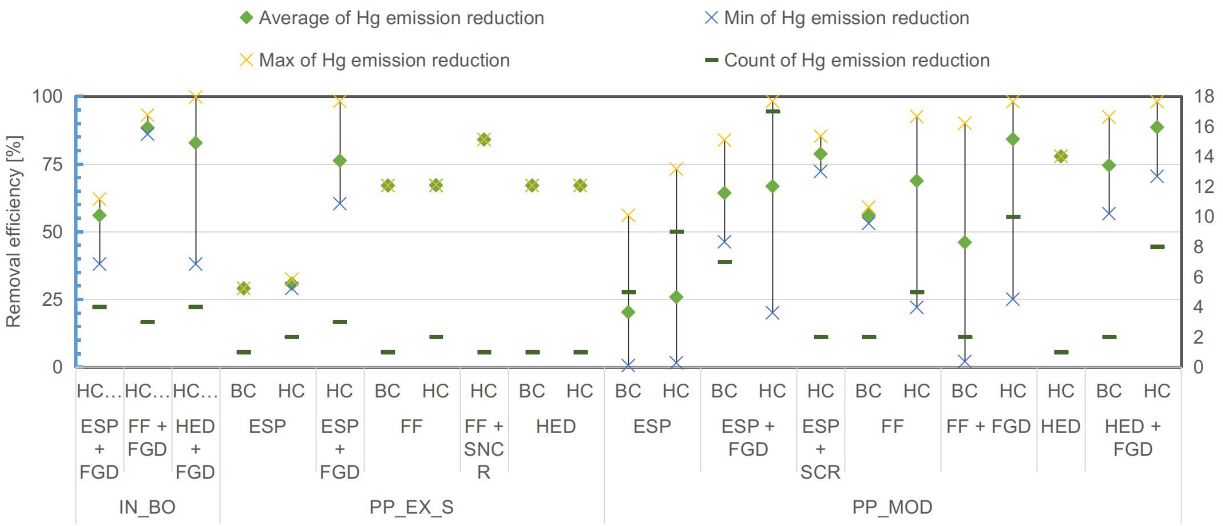

Figure 6: Literature values of control efficiencies for all co-benefit based options for coal-fired power generation. IN_BO ... industrial boilers, PP_EX_S ... coal power plant <50 MW, PP_MOD ... modern PP

[3] http://www.sulphuric-acid.com/techmanual/gascleaning/gcl_hg.htm

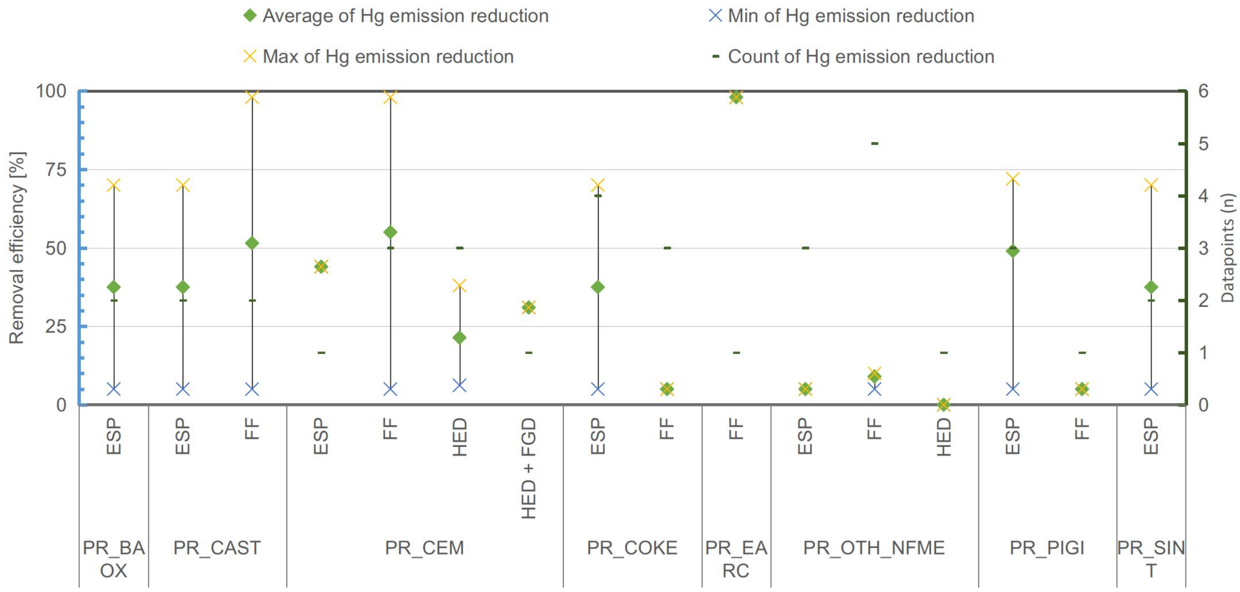

Figure 7: Literature values of control efficiencies values for all co-benefit based control options in the production sector. PR_BAOX ... basic oxygen furnaces, PR_CAST ... cast iron production, PR_CEM ... cement production, PR_COKE... coking plants, PR_EARC, electric arc furnace, PR_OTH_NFME ... non-ferrous metal production, PR_PIP ... pig iron production, PR_SINT ... sinteing plant.

Table 65: Aggregation of SO2 and combined PM+SO2 technologies from literature into GAINS categories.

Technology	**Description**	**Sector**	**Reported by**	**Aggregated into GAINS category:**
DFGD	Dry flue gas desulfurization	PP, PR, IN, CON		FGD
WFGD	Wet flue gas desulfurization	PP, PR, IN, CON		FGD
SDA	Spray-dry absorber	PP, PR, IN, CON		FGD
PM control + FGD	PM control combined with flue gas desulfurization (all types)	PP, PR, IN, CON		FF_FGD
PM control + FGD+SCR	PM control combined with all types of FGD and selective catalytic reduction	PP, PR, IN, CON		FF_FGD
PM control + FGD+SNCR	PM control combined with all types of FGD and selective non-catalytic reduction	PP, PR, IN, CON		FF_FGD
DC+FGS+ESD+APD	Combined PM+SO2 control	AU_LGP	Wu et al. (2018a)	HED_FGD

Note on denitrification techniques

Denittrification of power stations, such as by selective catalytic reduction or selective non-catalytic reduction, was not added to this report as a separate Hg removal technology, despite the proven impact on Hg control. The reasons for this are twofold: 1) SCR does not remove Hg from the power station, but rather is capable of

oxidizing Hg^0 to Hg^{II}, which in turn has a higher capture efficiency in PM and SO_2 control. 2) SCR is, in most cases, installed in facilities which also possess PM and SO2 control.
Li et al. (2020) collected plant-by-plant data on APCDs at coal-fired power stations, finding that the addition of SCR and SNCR to a PM+SO2 controlled plant added an average of 5% Hg removal efficiency. The presence of NOx control is not accounted for as a co-benefit, but rather, removal efficiencies at the higher end of the spectrum are assumed for PM+SO2 control options, to account for the presence of NOx control in some of these facilities.

Hg-specific end-of-pipe control options

Sorbent injection

Sorbent injection (SINJ) is the most common Hg-specific APCD. It has a low investment cost, with operation & maintenance costs depending on the type of sorbent, as well as sorbent dosage. SINJ requires subsequent dust control, preferably a fabric filter, but can be operated in the presence of existing ESP/HED as well. In cases of high Hg emissions, an additional fabric filter is installed. The GAINS category aggregates all types of sorbent injection. The most common are fly ash, zeolites, calcium hydroxide, activated carbon, activated coke, as well as Hg-optimised sorbents such as chlorinated, brominated and sulfated carbons (Dehoust et al., 2021b, p. 48-51). Injection of chlorine and bromine, which does not adsorb but rather oxidise present Hg^0, is included in this category due to similar plant requirements, similar efficiencies and similar cost characteristics.

It is well-established in waste incinerators and used in power stations. Efficiency in the production sector, such as cement production or coking, depends on the installation of an additional filter to remove the Hg-contaminated sorbent, otherwise Hg is recycled within the facility without removal (e.g. Dehoust et al., 2021b).

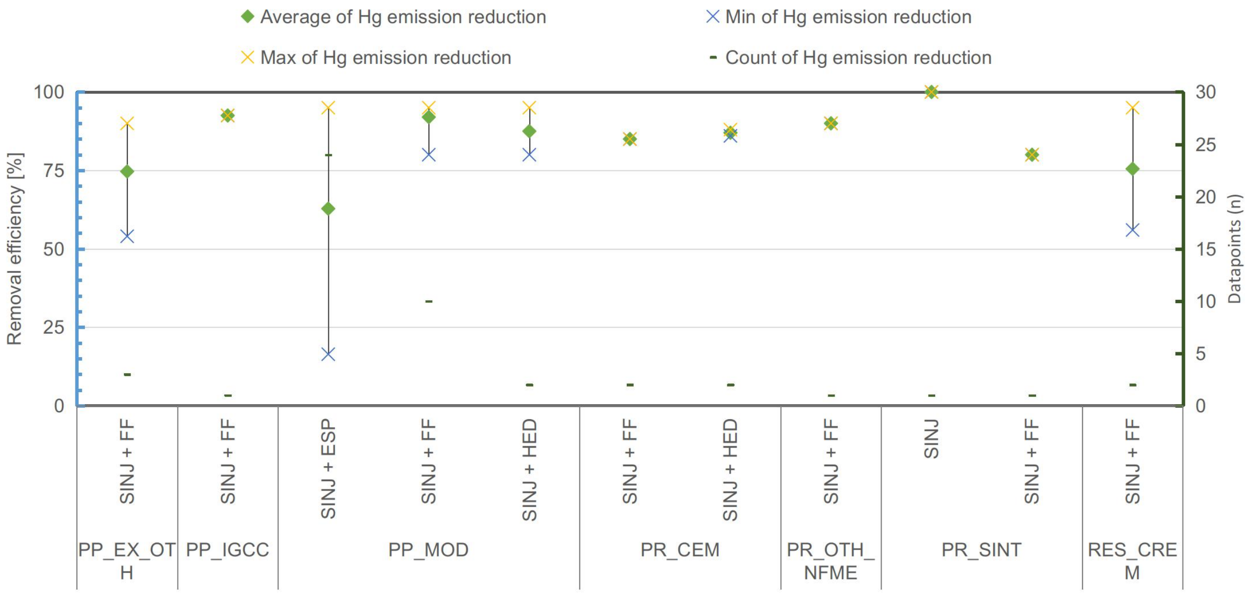

Figure 8: Literature values on different sorbent injection options across all relevant sectors. Raw data in SI.

Table 7: Aggregation of different Hg control technologies into the Sorbent Injection category.

Commonly used abbreviation	Technology description	Sector	Reported by	Aggregated into GAINS category:
DC+FGS+ESD+APD	Combined PM+SO2 control	PR_NFME	Wu et al. (2018a)	FFSINJ
DC+FGS+ESD+APD+DFGD	Combined PM+SO2 control	PR_NFME	Wu et al. (2018a)	FFSINJ
DC+FGS+ESD+APD+WFGD	Combined PM+SO2 control	PR_NFME	Wu et al. (2018a)	FFSINJ
DC+FGS+ESD+APS	Combined PM+SO2 control	PR_NFME	Wu et al. (2018a)	HEDSINJ
AC	Activated Carbon	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	AC injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	Brominated AC injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	Chlorinated AC injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	Sulfated AC injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	Cl injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	Br injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	Activated Coke injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	Calcium Hydroxide injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ
	Zeolite sorbent injection	PP, PR, IN, CON	Dehoust et al. (2021b)	SINJ

Stationary sorbent units

Stationary sorbent units or sorbent polymer catalyst units (SPC) are one of the few Hg-specific removal techniques where Hg is permanently bound in the filter unit for long-term disposal without leaching. This technology is sparsely applied in CFPPs, waste incinerators and copper smelters, but its high investment costs compared to co-benefit techniques and missing monetary incentive for permanent Hg storage make it a "future technology" that is not attractive yet.

Boliden Norzinc Process

The Boliden Norzinc Process (BNP) is a Hg removal process based on calomel Hg_2Cl_2 that is specific to acid plants in copper, lead and zinc smelting and mining. Selenium filters, designed for the same purpose with similar efficiencies, are also aggregated into this category. High bulk removal efficiencies of 71-95% are reported for both technologies. They are commercially applied where the production of high-quality Hg-free sulfuric acid is required (Dehoust et al., 2021b; Knabel, 2018).

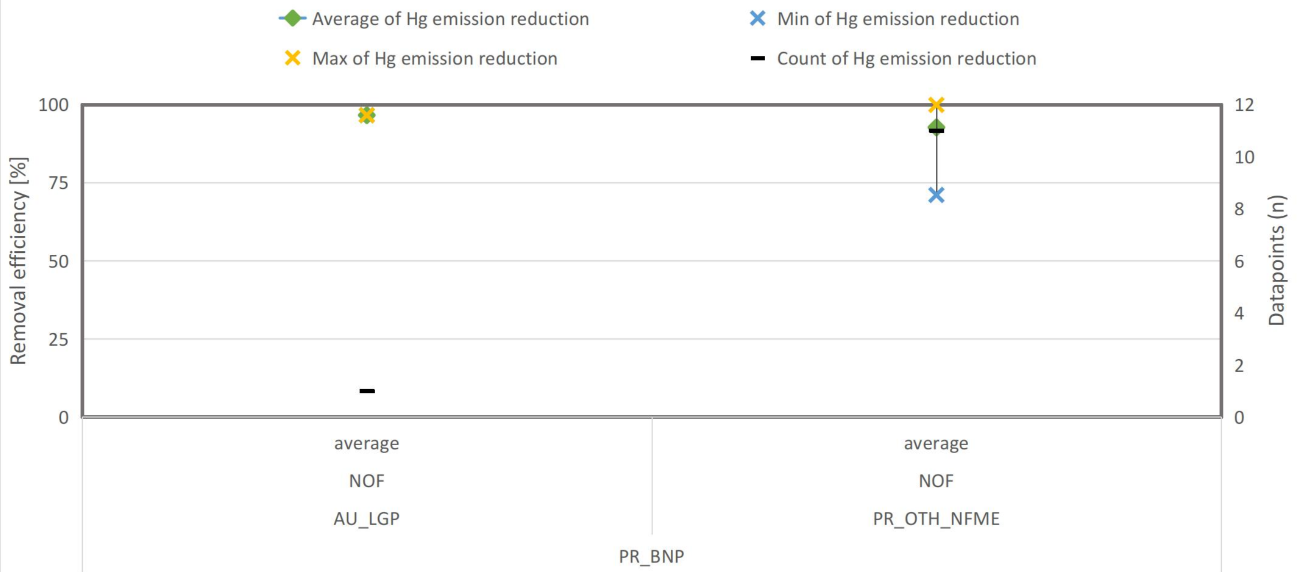

Figure 9: emoval efficiencies of the BOliden-Norzinc process smelting. AU_LGP ... large-scale gold production, PR_OTH_NFME ... non-ferrous metal production.

Table 8: Aggregation of different Hg removal technigues in the smelting sector into PR_BNP

Technology	**Description**	**Sector**	**Reported by**	**Aggregated into GAINS category:**
APD	Acid plants with double conversion, double absorption	PR_NFME	Wu2018a	PR_BNP
SMR	Specific mercury reduction	PR_NFME	Wu2018a	PR_BNP
DC+FGS+ESD+SMR+APD+DFGD	Combined PM+SO2 + Hg-specific control	PR_NFME	Wu2018a	PR_BNP
APS	Acid plants with single conversion, single absorption	PR_NFME	Wu2018a	PR_BNP
SF	Selenium filter	PR_NFME	UBA-DE 2021/1	PR_BNP

Other measures

In some sectors, Hg reduction can be achieved by implementing good practice in maintenance and optimised plant operation, rather than installation of additional technology. Such categories are represented as Good Housekeeping (GHIND) for the diesel generator sector (PP_ENG), as well as Good Practice (GP) in gold mining (MINE_GP), chlor-alkali production (PRF_GP1, PRF_GP2). Good practice in storage and handling (STH_GP) is also implemented for these sectors.

Scenario Development

As the co-benefit of Hg removal from traditional PM and SO_2 control is now automatically computed in GAINS, scenario conception in this report focused on improving the representation of Hg controls for an IEA World Energy Outlook 2016 dataset and a coal phase-out scenario, as well as exploring likely options for the implementation of the Minamata Protocol in China until 2050, and a maximum feasible reduction scenario, where newly added, Hg-specific controls are employed across all sectors, regardless of cost.

Table 9: Scenario overview.

	Scenario name	Description	Policy-relevant guiding question
1.	Current Legislation Scenario (CLE)	Hg-specific amendments to multi-pollutant World Energy Outlook scenarios in GAINS	Can stringent emission targets be met just through the use of co-benefit technologies?
2.	CLE + Minamata Scenario	A current legislation scenario, assuming the application of BAT/BEP technologies and process phase-outs as mandated by the full implication of the minamata protocol.	What Hg emission trajectory is China on, considering commitments resulting from the Minamata convention?
3.	Coal Phase-out Scenario	Coal-fired power generation is phased out, Hg control otherwise like CLE scenario.	Currently, coal combustion is a large source of Hg emissions. How will the “modal split” of Hg emissions change in a post-coal or zero-carbon world?
4.	Maximum Feasible Reduction (MFR) Scenario	Maximum feasible application of the technologies with highest removal efficiencies in each sector.	What Hg reduction can be achieved using the currently available technologies, disregarding any cost considerations?

For specific scenario design, primary and secondary sources, such as the Minamata Convention on Mercury texts and, other modelling studies, and expert literature on technology readiness and application, were consulted. The focus was on Hg-specific measures, as multi-pollutant controls are already represented in existing scenarios in GAINS. However, compared to the last release of GAINS (GAINS 3), the new implementation in GAINS4 includes extended options to picture co-benefits between PM and SO2 control, as pictured in the schematic in *Table 12*.

Current Legislation Scenario

The following Hg-specific updates to the current legislation scenario were conducted:

1. Chlor-alkali production using Hg cells is phased out.
2. Fabric filter-sorbent injection is applied in waste incineration.
3. Some smelting activities are equipped with the BNP process for higher quality of the sulfuric acid byproduct.

Significant further reduction of Hg emissions are expected in the CFPP sector, as the closure of small inefficient CFPP units, retrofitting of PM, SO_2 and NOx control, as well as more efficient fuel use thanks to the 12th Five-Year-Plan have been quantified to have avoided 23.51 tons of Hg emissions betwen 2011-2015, equivalent to 114 avoided deaths (Li et al., 2020). Consequently, it is possible that the main source of Hg releases to the air in China will shift to the production sector, which includes cement production and metal smelting.

Minamata Scenario

This scenario is based on the assumption of compliance with the Minamata convention.
The Minamata Convention takes a direct approach to regulating trade of Hg, as well as eliminating intentional uses of Hg in consumer products. Unintentional emissions of Hg such as from mining activities, the power sector and from waste, are controlled on a BAT/BEP basis, where it is up to individual countries to set their own national targets based on this suite of guidance. In the industrial and energy sectors, Hg emissions are strongly influenced on air pollution control measures which are targeted at “traditional” pollutants such as NOx, SO_2 and particulate matter. These are of special interest in economies where clean air is currently a high political priority, such as China. In the manufacturing industry, additionally to air pollution control, parties to the Minamata convention have agreed to phase out or reduce processes which are catalyzed by Hg and several products which contain the metal, for which other production methods exist (UNEP, 2013). It is estimated that artisanal and small-scale gold mining (ASGM) is currently the biggest primary Hg emission source to the atmosphere (AMAP/UNEP, 2019), but these estimates have large uncertainties due to the informal nature of the sector, so the first requirement of ratifying countries under MInamata is sector formalisation, followed by the production of a national action plan (Hilson et al., 2018; UNEP, 2013). While the Minamata Convention on Mercury calls for environmentally sound disposal of mercury-contaning wastes according to the Basel Convention Technical Guidelines, and these include a number of technical solutions for stabilisation of Hg wastes via sulfidation, amalgamation or even deep underground storage for wastes above 1000 mg kg^{-1} Hg content (Basel convention, see e.g. Chalkidis et al. 2020), this is not explicitly represented in Hg-GAINS yet. It is assumed that controlled landfilling has no atmospheric Hg (re-)emissions associated to it, implicitly including Hg-specific disposal methods in this option. Hg emissions are only associated with flaring.
Table 105 contains the sources used in constructing a realistic Minamata-compliant scenario for China. Lin et al. (2017) have assessed the Minamata commitments from a Chinese perspective, identifying existing policies and major compliance hurdles (see Table 9)

Table 10: Overview of the operational articles in the Minamata Convention and the relevance for China. From: Lin et al. (2017).

Article no.	Content	Existence of policy	Major compliance hurdles
Article 3	Supply and trade	No	Illegal mining, stocks unknown
Article 4	Hg-added products	Yes/No	Medical devices
Article 5	Manufacturing	Yes	Hg-containing catalysts
Article 7	ASGM[a]	Yes	No significant ASGM activity in China
Article 8	Emissions	Yes	BAT/BEP, monitoring
Article 9	Release	Yes	Lack of inventory
Article 10	Interim Hg storage	No	Law enforcement
Article 11	Hg-containing wastes	Yes	Law enforcement
Article 12	Contaminated sites	Yes	Large capital demand

[a]ASGM, Artisanal and Small Scale Gold Mining.

Table 11: Measures of the Minamata convention, including their applicability to GAINS.

Minamata Convention	**Nat'l Action Plan**	**Reduce**	**Ban**	**BAT / BEP**	**Description**	**GAINS implementation**
Article 3: Supply, Sources & Trade	x		2032 (mining)		Extensive import / export and mining bans	indirect
Article 4: Hg-added products	x	2020				indirect
Article 5: Manufacturing processes in which Hg or Hg compound s are used	x	2020 (-50%)	2018 (acetaldehyde) 2025 (chlor-alkali)	x,	Hg-based catalysts phased out, alternative processes adopted	PR sector
Article 7: Artisanal and small-scale gold mining	x	~			Sector formalization	AU sector
Article 8: Emissions	x			x		PP, IN, CON, PR sectors
Article 9: Releases to water and land	x			x	Reduce & control	indirect
Article 10: Environmentally sound interim storage	x			x		indirect
Article 11: Wastes	x			x	Basel Convention	indirect
Article 12: Contaminated Sites	x			x		indirect

Table 12: Sources used for constructing a realistic Minamata-compliant scenario for China:

Sector	Data source	Scenario description
Coal-fired power plants	Giang et al. (2015), Wu et al. (2018a)	
Non-ferrous metal production	Wu et al. (2018b), Unep (2021)	
Waste sector	Wu et al. (2018a), Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (1989)	
Artisanal and small-scale gold mining		Hardly applicable in China --> no Hg-specific scenarios
Industrial boilers	Lin et al. (2017)	No planned APCDs reported by Lin et al. (2017) in China --> no Hg-specific scenarios

Maximum Feasible Reduction Scenario

The MFR scenario assumes Hg-controls in every sector where this is applicable, while sticking with energy projections from the World Energy outlook. According to research conducted for this report, not all sectors will realistically be covered with Hg-specific control options, so the burning of non-fossil fuels (except waste), domestic combustion, coal mining, storage and handling, as well as the agriculture sector are covered with conventional APCDs or no control options related to Hg reduction (see Table 12). Sectors which are difficult to regulate with technological solutions, e.g. ASGM, or which will be phased out due to especially high Hg emissions, such as certain production processes like chlor-alkali production and Hg-based catalysts, are projected to be banned altogether.

Coal Phase-Out Scenario

As an entry point into projecting Hg emissions under stringent future climate policy, the coal phase-out scenario is conceptualised. Here, Hg controls are mostly due to co-benefits, like in the CLE scenario, but coal combustion in power plants and industrial boilers is banned, leading to a likely shift in emissions. Several synthesis reports, such as the Emissions Gap Report 2017 (UNEP, 2017) have stated that early retirement or complete phase-out of coal-fired power is necessary in order to achieve compliance with the Paris Climate Agreement and the target of an average global warming of 1.5°C (Yanguas Parra et al., 2019; UNEP, 2017). For this scenario, the coal phase out dates will be adopted based on their compliance with the Paris Agreement, and it is assumed that reductions of 90% of coal use will happend in 2030 in the EU28 and the OECD, 2040 in China, and 2050 in the rest of the world (Yuanguas Parra et al., 2019).

Table 13: Overview of Hg-reduction measures in different sectors. ASGM ... Artisanal and small-scale gold mining. PM ... Hg reduction achieved through co-benefits with particulate matter (PM) control. PM+SO2 ... Hg reduction achieved through co-benefits with PM and SO2 abatement technologies. Hg ... Hg-specific Hg control option. BAN ... Ban of the emission source leads to 100% abatement efficiency.

		GAINS3	GAINS 4	GAINS 4	GAINS 4	GAINS 4
		IEA World Energy Outlook 2016, Current Legislation		CLE + Minamata commitments	Maximum Feasible Reduction	Coal Phase-out
Power plants	Coal fired	PM+SO2	PM+SO2	PM+SO2	Hg	BAN
	Biomass & other fuels	PM	PM	PM	PM	PM
Other combustion	Domestic	PM	PM	PM	PM	PM
	Industrial boilers	PM+SO2	PM+SO2	PM+SO2	Hg	BAN
	Conversion	PM				Hg
Production	Brick, fertilizer, glass, lime, coke, paper, oil	PM	PM+SO2	PM+SO2	Hg	PM+SO2
	Cement production					
	Chlor-alkali production	BAN	BAN	BAN	BAN	BAN
	Other (PVC)	N/A	N/A	Hg	Hg	Hg
Mining, metals	Mining (coal, etc.)	NOC	NOC	NOC	NOC	NOC
	Non-ferrous metal production	Hg	Hg	Hg	Hg	Hg
	Al, iron&steel	PM	PM+SO2	PM+SO2		PM+SO2
	Large-scale gold production	NOC	NOC	NOC		NOC
Waste	Cremation	PM	PM	NOC	Hg	NOC
	Waste disposal	NOC	NOC	Hg		
	Waste to Energy	Hg	Hg			Hg
ASGM	Artisanal and small-scale gold production	NOC	NOC	Hg	BAN	NOC
Others	Transport	PM	PM	PM	PM	PM
	Storage and handling	NOC	NOC	NOC	NOC	NOC
	Agriculture	NOC	NOC	NOC	NOC	NOC

Discussion

State of available data

End-of-pipe options for flue gas Hg control options are highly dependent on the chemical conditions inside an individual industrial facility, such as temperature, presence of other chemical substances such as ash, halogens, sulphur, water vapor, as well as APCDs for particulate matter, SO_2 and NOx control. Where removal efficiencies are available, these are often not speciated, and can thus not be directly compared to the GAINS numbers, which depend on educated guesses of the proportion of $Hg^0/Hg^{II}/Hg^p$ emitted from a facility. Even current BAT/BEP guidance published by UNEP (2019) refrains from putting global reduction efficiencies on the recommended BAT/BEP technologies. As such, as demonstrated in the collected data, uncertainties on emission estimates are exceptionally high. There is currently no capacity to regionalize the removal efficiencies for different technologies, but this might be a relevant endeavor if Hg-GAINS is used in case studies. The GAINS Hg control options are aggregates of many separate technologies, often exhibiting broadly similar removal efficiencies, but the accuracy of the values may be significantly improved if preferred technology options and their removal efficiencies would be implemented in the regionalized control options.

Acknowledging Hg cycling through different emission sources: Limitations of GAINS for the representation of Hg emissions

Despite the obvious merits of using GAINS to represent all Hg emission sources to air due to its ease of handling and policy importance, there are some significant drawbacks to the method when looking at mercury cycling through the environment, as well as through our industry. Notably, only some control options present true sinks of Hg, where long-term storage of the metal can be assured without leaching (e.g. the use of SPC technologies, BNP, or disposal of Hg-contaminated dust control in hazardous landfills). However, the reality of many Hg co-benefit control options is the redirection of Hg from direct emissions to the atmosphere into temporary stores or sinks,or aqueous waste streams (e.g. FGD slurry). Some of these, like fly ash or FGD slurry, are the re-used in other industrial processes like cement or gypsum production, leading to alleviated Hg levels there, and often to re-emission. These feedbacks between Hg stocks in different industry sectors are not represented by Hg control strategies in GAINS, but rather as Hg emission factors of a certain fuel-sector-control option combination, and are technically fixed. These emission factors might need adjusting in co-benefit scenarios, to account for higher Hg emissions e.g. in certain production sectors like cement production. Additionally, they might lead to structural changes in some industries. It is reported that when FGD slurry exceeds maximum permissible Hg levels, it is not used for gypsum production anymore, but the industry chooses to use natural, mined feedstocks instead (Dehoust et al. 2021b).

Outlook/ Further Improvements

Hg-specific control strategies in the waste sector

While the Minamata Convention on Mercury calls for environmentally sound disposal of mercury-contaning wastes according to the Basel Convention Technical Guidelines, and these include a number of technical solutions for stabilisation of Hg wastes via sulfidation, amalgamation or even deep underground storage for wastes above 1000 mg kg^{-1} Hg content (Basel convention, 1989, Chalkidis et al., 2020), this is not explicitly represented in Hg-GAINS yet. It is assumed that controlled landfilling has no atmospheric Hg (re-)emissions associated to it, implicitly including Hg-specific disposal methods in this option.

Data improvements:

- Distinguish between pulverised coal, others in efficiencies of APCDs (see e.g. Zhang, 2016)
- Update of emission factors and emission speciation (in all sectors)
  - Review of speciation of emissions, for possible coupling to GEOS-Chem model(Zhang et al., 2015), NFME-acid plants (Takaoka et al., 2016)
- If Hg-GAINS is to be maintained on the long term, it would be worth to look into regionalising the emission factors, as well as the efficiencies of different technologies, taking into account factors such as local prevalences in coal types or ESP/FGD types.
- Research effect of CCS installations on Hg capture efficiency.

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Appendix

Table A1: Removal efficiencies of Hg abatement technologies, organised by GAINS categories and sectors.

Sector IDSEC	Fuel IDACT	Control IDTECH	Hg removal efficiency Mean [%]	Min. [%]	Max. [%]	Datapoints [n]	Reference
AU_LGP							
	NOF	PR_BNP	96.5	96.5	96.5	1	Wu2018a
IN_BO							
	HC,	ESP_FGD	56	38	62	4	Wu2018a
	HC,	FF_FGD	88.3	86	93	3	Wu2018a
	HC,	HED_FGD	82.8	38	99.7	4	Wu2018a
	HC,	PR_WSCRB	23	23	23	1	Wu2018a
	HC,	PR_WSCRB_	62	62	62	1	Wu2018a
PP_EX_OT							
	OS2	FFSINJ	74.7	54	90	3	Wu2018a UBA-DE 2021/2 GORE2020
PP_EX_S							
	BC						
	BC	ESP_FGD	76.2	60.3	98.1	3	LiJiashuo2020
	BC	ESP_REM	30.7	29	32.4	2	Zhang2016, LiJiashuo2020,
	BC	FF_REM	67.1	67	67.2	2	Zhang2016, LiJiashuo2020
	BC	FF_SCR	84	84	84	1	LiJiashuo2020
	BC	HED_REM	67	67	67	1	Zhang2016
	HC	ESP_FGD	76.2	60.3	98.1	3	LiJiashuo2020
	HC	ESP_REM	30.7	29	32.4	2	Zhang2016, LiJiashuo2020
	HC	FF_REM	67.1	67	67.2	2	Zhang2016, LiJiashuo2020
	HC	FF_SCR	84	84	84	1	LiJiashuo2020
	HC	HED_REM	67	67	67	1	Zhang2016
PP_IGCC							
	HC	FFSINJ	92.5	92.5	92.5	1	NETL
PP_MOD							
	BC	ESP_FGD	68.8	46.2	98.1	12	Pacyna2010, Liu2018, Giang2015, iPOG, LiJiashuo2020
	BC	ESP_REM	22.3	0.5	56	6	NA, Pacyna2010, Giang2015, iPOG, LiJiashuo2020
	BC	ESP_SCR	78.7	72.2	85.2	2	LiJiashuo2020
	BC	ESPSINJ	64.6	48.3	87.1	12	Feeley2009, iPOG
	BC	FF_FGD	72.8	2	90	6	Pacyna2010, Giang2015, LiJiashuo2020
	BC	FF_REM	59.7	53	67.2	3	NA, iPOG, LiJiashuo2020,
	BC	FFSINJ	90	80	95	6	Feeley2009, iPOG
	BC	HED_FGD	87.5	56.6	97.5	5	Liu2018, LiJiashuo2020
	BC	HED_REM	77.8	77.8	77.8	1	LiJiashuo2020
	BC	LHGCO	19.5	3.4	40	4	NA, iPOG, UBA-DE 2021/2
	BC	LHGCO_ESP	70.5	70.5	70.5	1	Giang2015,
	BC	LHGCO_FGD	90	90	90	1	UBA-DE 2021/2
	BC	LHGCO_PM	30.9	0.5	58	9	Giang2015, iPOG
	BC	NOC	0.5	0.5	0.5	1	iPOG
	BC	SCR	84.5	84.5	84.5	1	UBA-DE 2021/2
	BC	WSCRB	49.7	49.7	49.7	1	iPOG,
	HC	ESP_FGD	66.7	20	98.1	17	Pacyna2010, Liu2018, Giang2015, Giang2015, from Wang2010, iPOG, LiJiashuo2020
	HC	ESP_REM	25.8	1.5	73.1	9	Pacyna2010, Liu2018, Giang2015, iPOG, LiJiashuo2020
	HC	ESP_SCR	78.7	72.2	85.2	2	LiJiashuo2020
	HC	ESPSINJ	61.0	16.4	95	12	Feeley2009, iPOG
	HC	FF_FGD	84.1	25	98	10	Pacyna2010, Liu2018, Giang2015, LiJiashuo2020
	HC	FF_REM	68.7	22	92.5	5	NA, Pacyna2010, iPOG, LiJiashuo2020
	HC	FFSINJ	95	95	95	4	iPOG
	HC	GHIND_HG	50	50	50	2	Feeley2009
	HC	HED_FGD	88.5	70.4	98	8	Liu2018, LiJiashuo2020
	HC	HED_REM	77.8	77.8	77.8	1	LiJiashuo2020
	HC	HEDSINJ	87.5	80	95	2	Wilcox2015
	HC	LHGCO	29.1	21.2	40	4	NA, iPOG, UBA-DE 2021/2
	HC	LHGCO_ESP	70.5	70.5	70.5	1	Giang2015
	HC	LHGCO_FGD	90	90	90	1	UBA-DE 2021/2
	HC	LHGCO_PM	30.3	17	58	9	Giang2015, iPOG,
	HC	NOC	0.5	0.5	0.5	1	iPOG
	HC	SCR	84.8	84.5	85	2	NA, UBA-DE 2021/2,
	HC	WSCRB	38.9	9	68.8	2	Pacyna2010, iPOG,
	HC	WSCRB_FGD	11	10	12	2	Pacyna2010

PR_BAOX							
	NOF	PR_ESP_RE	37.5	5	70	2	Pacyna2010 / EU-ESPREME
	NOF	PR_WSCRB	8	8	8	1	Pacyna2010 / EU-ESPREME
PR_CAST							
	NOF	PR_ESP_RE	37.5	5	70	2	Pacyna2010 / EU-ESPREME
	NOF	PR_FF_REM	51.5	5	98	2	Pacyna2010 / EU-ESPREME
PR_CEM							
	NOF	PR_ESP_RE	44	44	44	1	Wu2018a
	NOF	PR_FF_REM	55	5	98	3	Wu2018a, Pacyna2010 / EU-ESPREME
	NOF	PR_FFSINJ	68.8	52.5	85	2	UBA-DE 2021/2
	NOF	PR_FGD	90	90	90	1	Pacyna2010 / EU-ESPREME
	NOF	PR_HED_FG	31	31	31	1	Wu2018a
	NOF	PR_HED_RE	21.4	6.2	38	3	Wu2018a
	NOF	PR_HEDSINJ	87	86	88	2	Wu2018a
PR_COKE							
	NOF	PR_ESP_RE	37.5	5	70	4	Pacyna2010 / EU-ESPREME
	NOF	PR_FF_REM	5	5	5	3	Pacyna2010 / EU-ESPREME
	NOF	PR_FGD	35	30	40	2	Pacyna2010 / EU-ESPREME
	NOF	PR_LHGCO	5	5	5	1	Pacyna2010 / EU-ESPREME
PR_EARC							
	NOF	PR_FF_REM	98	98	98	1	Pacyna2010 / EU-ESPREME
PR_OTH_N							
	NOF	NOC	0.5	0.5	0.5	1	Wu2018a
	NOF	PR_BNP	92.6	71	99.8	11	Wu2018a, UBA-DE 2021/1
	NOF	PR_CYC	5	0	10	2	Wu2018a, UBA-DE 2021/1
	NOF	PR_ESP_RE	5	5	5	3	Pacyna2010 / EU-ESPREME
	NOF	PR_FF_REM	9	5	10	5	Pacyna2010 / EU-ESPREME
	NOF	PR_FFSINJ	90	90	90	1	Pacyna2010 / EU-ESPREME
	NOF	PR_HED_RE	0	0	0	1	UBA-DE 2021/1
	NOF	PR_SPC	70	70	70	1	GORE2020
PR_OTHER							
	NOF	PR_CYC	10	10	10	1	UBA AT 2007
PR_PIGI							
	NOF	PR_ESP_RE	49	5	72	3	Pacyna2010 / EU-ESPREME
	NOF	PR_FF_REM	5	5	5	1	Pacyna2010 / EU-ESPREME
PR_SINT							
	NOF	PR_ESP_RE	37.5	5	70	2	Pacyna2010 / EU-ESPREME
	NOF	PR_FFSINJ	80	80	80	1	Pacyna2010 / EU-ESPREME
	NOF	PR_SINJ	100	100	100	1	Pacyna2010 / EU-ESPREME
	NOF	Pacyna2010 /	100	100	100	1	
RES_CREM							
	NOF	FFSINJ	75.5	56	95	2	Schetter/Bittig2020

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Table A2: Cost data on sorbent injection technologies.

Sector*	Fuel**	Technology / tech combination	MW (el)	achieved reduction [%]	Sorbent ***	sorbent price [Eur/Mg] or unit price [dimensions]	cost of sorbent [MEur/a] or unit [MEur]	amount of sorbent/unit needed [Mg/a]	(sorbent) cost per ton Hg abated	Operation and Maintenance [MEur/a]	total investment costs [MEur]	Capital investment costs INV_C [EURO/kW th for PP, Meur/unit for PR]	INV_C Unit	INV_C in EUR/kW	Fixed O&M costs FO_M [%/year]	FO_M unit	Source / Comment 1	Comment 2: Specific requirements
PP	BC, HC	SINJ after ESP (cost of ESP not considered)	250	70	AC	870-2110 $/kg.						3.16	$/kW	2.31	324.30	% of INV_C/year	UNEP2016BATBEP, p.29; 2007 dollars - Table 11, right column	
PP	BC, HC	SINJ after FF/HED (cost of FF/HED not considered)	250	90	AC	870-2110 $/kg.						3.16	$/kW	2.31	100.76	% of INV_C/year	UNEP2016BATBEP, p.29; 2007 dollars - table 11, left column	
PP	BC, HC	Activated Carbon Injection	500		AC	870-2110 $/kg.						2-5	$/kW	2.55	0.03-0.1	$/kW/a	UNEP2016BATBEP, p.28; 2007 dollars	
PP	BC, HC	Activated Carbon Injection	700		AC	870-2110 $/kg.						2-5	$/kW	2.55	0.03-0.1	$/kW/a	UNEP2016BATBEP, p.28; 2007 dollars	
PP	BC, HC	Activated Carbon Injection	300		AC	870-2110 $/kg.						2-6	$/kW	2.92	0.03-0.1	$/kW/a	UNEP2016BATBEP, p.28; 2007 dollars	
PP	BC, HC	Activated Carbon Injection	100		AC	870-2110 $/kg.						3-8	$/kW	4.01	0.03-0.1	$/kW/a	UNEP2016BATBEP, p.28; 2007 dollars	
PP	HC	SINJ	500		AC	1100		150 mg /Nm3 wet	41800			5.40		5.40	0.80	Eur/MWh*a	summary of calculation by Ole Petzold, based on data from UBA-DE 2021/1	
PP	BC	SINJ	500		AC	1100		200 mg /Nm3	55000			5.40		5.40	1.02	Eur/MW	summary of calculation by Ole Petzold, based on data	

								wet								h*a	from UBA-DE 2021/1	
PP	BC, HC	FFSINJ	400	67	AC	500-2500	1-5.1	2000			3.4						UBA-DE 2021/2, p.48	
PP	HC	SCR + halogen addition + FGD	800	80	Br(CaBr2)	2310	130000	2.5-5 mg/kg dry coal			0.24 Mio Eur/a	0.30	EUR/kW/a				UBA-DE 2021/2, p.76, Andritz 2015a	low-Cl feedstock
PP	HC	SCR + halogen addition + FF	800	80	Br(CaBr2)	2310	130000	2.5-5 mg/kg dry coal			0.43 Mio Eur/a	0.54	EUR/kW/a				UBA-DE 2021/2, p.76, Andritz 2015a	low-Cl feedstock
PP	BC	halogen addition	800	80	Br(CaBr2)	2310	130000	25-50 mg/kg dry coal			0.94 Mio Eur/a	1.18	EUR/kW/a				UBA-DE 2021/2, p.76, Andritz 2015a	low-Cl feedstock
PP	BC	halogen addition	600	80	Br(CaBr2)	2310	130000	25-50 mg/kg dry coal		0.22 EUR/MWh	2200 EUR/MWh	#REF!	MEur		0.22	Eur/MW*a	UBA-DE 2021/2, p.76, TE Winkel 2014, Tebert et al 2016,	low-Cl feedstock
PP	HC	SINJ	500		brominated AC	2800		50 mg /Nm3 wet	36400			5.40		5.40	0.67	Eur/MWh*a	summary of calculation by Ole Petzold, based on data from UBA-DE 2021/1	
PP	BC	SINJ	500		brominated AC	2800		100 mg /Nm3 wet	70000			5.40		5.40	1.20	Eur/MWh*a	summary of calculation by Ole Petzold, based on data from UBA-DE 2021/1	
PR_CEM	NOF	FFSINJ			brominated AC	2250		70		160000								
PP	HC	FGD + bromAC	800		CaBr2			9		410000							UBA-DE 2021/2, p.63	
PP	BC	FGD + bromAC	800		CaBr2			9		1100000							UBA-DE 2021/2, p.63	
PP	BC, HC	FGD + bromAC	500		CaBr2						0.9-1.4						UBA-DE 2021/2, p.63 (STEAG-US 2015b)	
PP	HC	SINJ	500		lignite coke	300		250 mg /Nm3 wet	=63*P91 Eur/kg Hg (sorbent price)			5.40		5.40	0.57	Eur/MWh*a	summary of calculation by Ole Petzold, based on data from UBA-DE 2021/1	
PP	BC	SINJ	500		lignite coke	300		?	?			5.40		5.40	?	Eur/MWh*a	summary of calculation by Ole Petzold, based on data from UBA-DE 2021/1	
PP		"refined"coal (US market)		40	refined coal													
PP	HC	SPC	500		SPC	5000						32.00	Eur/kWth	32.00	0.69	Eur/MWh*a	summary of calculation by Ole Petzold, based on data from UBA-DE 2021/1	

PP	BC	SPC	500		SPC	5000						32.00	Eur/kWth	32.00	0.91	Eur/MWh*a	summary of calculation by Ole Petzold, based on data from UBA-DE 2021/1	
PP_EX_OTH	OS2	AC, no FGD, no filter			sulfated AC	400-2000		200			0.05 - 0.1						UBA-DE 2021/2, p.48 (Esser-Schmittmann 2014a)	
PP_EX_OTH	OS2	FFSINJ			sulfated AC	400-2000		30			0.05 - 0.1						UBA-DE 2021/2, p.48 (Esser-Schmittmann 2014a)	
CON_COMB	BC, HC	FGD + sulf		75	sulfidic precipitation agent TMT15	1200		40 mg per kg coal									UBA-DE 2021/2, p.63, Schuetze 2016b)	

*PP ... coal-fired power plant, PR_CEM ... cement production, PP_EX_OTH ... waste incineration, IN_BO ... industrial boiler) NFME ... non-ferrous metal smelting, CON .. conversion sector

**BC ... browon coal, HC ... hard coal, OS2 ... waste

***AC ... Activated carbon

Table A3: Preliminary collected cost data.

Sector*	Fuel**	Technology / tech combination	[MW (el)]	achieved reduction [%]	Lifetime of unit [a]	Operation and Maintenance [MEur/a]	portioning mechanism, tubing, lines etc [MEur]	total investment costs [MEur]	Capital investment costs INV_C	INV_C Unit	INV_C to EURO/kW (if year of price known, converted by that year	Variable investment costs INV_V [kEuro]	Fixed O&M costs FO_M [%/year]	FO_M unit	Byproduct BY_PROD [t/t Hg]	Reference / Comment 1	Coomment 2
PR		Activated Carbon Injection + FF		80	15								3.20	US$/t		****	2008 per t product, annualised to 15 yr lifetime
PR		Ca hydroxide-impregnated sorbents		100	15								2.30				US$ 2008 per t product, annualised to 15 yr lifetime
PP	HC, BC	Calcium injection in furnace + SNCR + circulating fluidized bed semi dry process + FF	330		>3				58.30	Eur/kW	58.30		2.15	Eur/MW*a		[1]	

PP	HC, BC	Calcium injection in furnace + SNCR + circulating fluidized bed semi dry process + FF	330		>3				58.30	Eur/kW	58.30		2.15	Eur/MW*a		[1]	
PP	HC	DFGD_HG, additives w/o ACI, DFGD, ESP present	500						5.00	$/kW	3.60	0.58 %/MWh	0.20		0	SL2011_IPMModel; 2009 dollars, table 5	
PP	HC, BC	ESP + ammonium desulfurization + SNCR	300		>5				42.93	Eur/kW	42.93		1.64	Eur/MW*a		[1]	
PP	BC, HC	Fabric filter							55-70	$/kW	45.62		0.00			UNEP2016BATBEP, p.28; 2007 dollars	
IN_BO_S	HC, BC	FF+WFGD+LNP+SNCR	6		>3				193.27	Eur/kW	193.27		0.44	Eur/MW*a		[2]	
PP	BC, HC	FFSINJ														No negative effect for fly as benefit, as separate FF is installed	
PP	HC	FFSINJ, WFGD and ESP present, additional filter	500						155.00	$/kW	111.51	0.5 $/MWh	0.38		112.49 kg/hr	SL2011_IPMModel; 2009 dollars, table 3	
PP_EX_L		Hg-optimised SCR	500	85			2.11									UBA-DE 2021/2, p.80, Schuetze 2016b	
PR_CEM or CON_COMB?	HC, BC	LPN+SNCR+WFGD+ESP	12		>4				11.70	Eur/kW	11.70		0.07	Eur/MW*a		[1]	
PP	HC, BC	SCR	2000						8.08	Eur/kW	8.08					[2]	
PP	HC, BC	SCR	1320						9.34	Eur/kW	9.34					[2]	
PP	HC, BC	SCR	700						11.45	Eur/kW	11.45					[2]	
PP	HC, BC	SCR+WFGD+ESP	1000		>11				11.18	Eur/kW	11.18		5.14	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	1000		>11				11.18	Eur/kW	11.18		4.93	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	1000						11.18	Eur/kW	11.18		5.14	Eur/M		[2]	

														Wh			
PP	HC, BC	SCR+WFGD+ESP	1000						11.18	Eur/kW	11.18		4.93	Eur/MWh		[2]	
CON?	HC, BC	SCR+WFGD+ESP	300		>7				17.33	Eur/kW	17.33		0.39	Eur/MW*a		[1]	
IN_BO_CHEM	HC, BC	SCR+WFGD+ESP	300		>7				17.33	Eur/kW	17.33		0.39	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	330		>19				29.27	Eur/kW	29.27		1.94	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	330		>19				29.27	Eur/kW	29.27		2.07	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	330						29.27	Eur/kW	29.27		1.94	Eur/MW		[2]	
PP	HC, BC	SCR+WFGD+ESP	330						29.27	Eur/kW	29.27		2.07	Eur/MWh		[2]	
IN_BO_CHEM	HC, BC	SCR+WFGD+ESP	12		>7				108.33	Eur/kW	108.33		0.26	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	33		>10				315.15	Eur/kW	315.15		7.15	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	33		>9				315.15	Eur/kW	315.15		7.15	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	33		>9				315.15	Eur/kW	315.15		7.15	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	33		>9				315.15	Eur/kW	315.15		7.15	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	10.2		>7				509.80	Eur/kW	509.80		0.39	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	33		>14				1003.76	Eur/kW	1003.76		26.05	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	33		>12				1006.91	Eur/kW	1006.91		26.05	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	33		>12				1006.91	Eur/kW	1006.91		26.05	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	64		>15				1012.92	Eur/kW	1012.92		26.05	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	64		>15				1012.92	Eur/kW	1012.92		26.05	Eur/MW*a		[1]	
PP	HC, BC	SCR+WFGD+ESP	33		>14				1448.83	Eur/kW	1448.83		26.05	Eur/MW*a		[1]	

CON?	HC, BC	SCR+WFGD+ESP	1.5		>7				3466.67	Eur/kW	3466.67		0.39	Eur/MW*a		[1]	
PP?	HC, BC	SCR+WFGD+ESP	1.5		>7				3466.67	Eur/kW	3466.67		0.39	Eur/MW*a		[1]	
IN_BO_CHEM	HC, BC	Sewage station	7.5		>8				52.00	Eur/kW	52.00		0.01	Eur/MW*a		[1]	
PP	HC	SINJ after ESP (cost of ESP not considered), in the presence of Wet FGD	500						9.00	$/kW	6.47	3.04 $/MWh	0.44		281.68 kg/hr	SL2011_IPMModel; 2009 dollars, table 1	
PP	HC	SINJ after FF/HED (cost of FF/HED not considered), WFGD, SCR present	500						7.00	$/kW	5.04	2.46 $/MWh	0.43		112.49 kg/hr	SL2011_IPMModel; 2009 dollars, table 2	
IN_BO_CHEM	HC, BC	SNCR+WFGD+ESP	?		>7				5.20	Meur			0.39	Eur/MW*a		[1]	
IN_BO_S	HC, BC	SNCR+WFGD+WESP	6		>3				368.33	Eur/kW	368.33		0.26	Eur/MW*a		[1]	
PP_EX_L	BC	SPC modules	500		10	0		8.5	17.00	Eur/kWth					0	UBA-DE 2021/2, p.70, Petzold 2018b	WFGD presence
PR_CEM		SPC modules		75	7	0		8-14	8-14	MEur						UBA-DE 2021/2, p.70, Petzold 2018b; data from pilot plants, it is a retrofittin gmeasure and currently only used in coal power stations.	low temp in flue gas
PR_CEM		SPC modules		90	8	0		9-15	9-14	MEur						UBA-DE 2021/2, p.70, Petzold 2018b	low temp in flue gas
PP_EX_L	HC	SPC modules	500	50	10	0		8.5								UBA-DE 2021/2, p.70, Petzold 2018b	
IN_NFM		SPC modules		75	10	0											low temp in flue gas
PP_EX_OTH	OS2	SPC modules		75	10	0											low temp in flue gas
PR_COKE		SPC modules		75	10	0											low temp in flue gas
PR_OT_NFME		SPC modules		75	10	0											low temp in flue gas

PP	HC, BC	subcritical units+LNB+SCR+ESP+Wet removal + seawater desulfurization	32		>4				288.88	Eur/kW	288.88		3.25	Eur/MW*a		[1]	
PP	HC, BC	subcritical units+LNB+SCR+ESP+Wet removal + seawater desulfurization	32		>4				288.88	Eur/kW	288.88		3.44	Eur/MW*a		[1]	
PP	HC, BC	Ultra Supercritical Unit+LNB+SCR+ESP+Wet removal + seawater desulfurization	68		>5				222.43	Eur/kW	222.43		7.79	Eur/MW*a		[1]	
PP	HC, BC	Ultra Supercritical Unit+LNB+SCR+ESP+Wet removal + seawater desulfurization	68		>5				222.43	Eur/kW	222.43		6.97	Eur/MW*a		[1]	
PR		use of low-Hg feedstock		5	as long as plant operates								0.20	US$ 2008 per t product, annualised to 15 yr lifetime			
PP, PR, DOM		washed coal (EU estimates)		30					0.00			0.0147 Eur/MWh				EU2005HgCostSmallComb, P.51, 2005 euros; reduction number frol Liu et al. 2021, UNEP2010	
PP	HC, BC	WFGD	2000						37.47	Eur/kW	37.47					[2]	
PP	HC, BC	WFGD	1320						41.68	Eur/kW	41.68					[2]	

PP	HC, BC	WFGD	700						49.49	Eur/kW	49.49					[2]	
PP	HC	WFGD_Hg, aditives w/o ACI, in presence of WFGD, ESP	500						6.00	$/kW	4.32	0.81 $/MWh	0.33		0	SL2011_IPMModel; 2009 dollars, table 4	

**PP ... coal-fired power plant, PR_CEM ... cement production, PP_EX_OTH ... waste incineration, IN_BO ... industrial boiler) NFME ... non-ferrous metal smelting, CON .. conversion sector*
***BC ... browon coal, HC ... hard coal, OS2 ... waste*
****AC ... Activated carbon*

[1]Hubei data from Sili Zhou, Jiashuo Li (pers.comm.) "Data for GAINS-0711-Cost.xls"; converted from RMB to Eur at 1 RMB = 0.13Eur (16.8.2021)
[2]non-region-specific data from Sili Zhou, Jiashuo Li (pers. Comm.), "Data for GAINS-0711-Cost.xls"; converted from RMB to Eur at 1 RMB = 0.13Eur (16.8.2021)