Inventory of U.S. sources of mercury emissions to the atmosphere

Yenaxika Bolate

Advisors: Profs. N.J. Themelis and A.C. Bourtsalas

Department of Earth and Environmental Engineering
Fu Foundation School of Engineering
Columbia University

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EXECUTIVE SUMMARY

The purpose of this study was to compile an inventory of 2014 mercury emissions to the atmosphere from all U.S. anthropogenic sources. Sources of particular interest were mercury emissions associated with the management of post-recycling municipal solid waste (MSW), i.e. waste to energy (WTE) plants and sanitary landfills.

The main sources of mercury emission data were the National Emissions Inventory (NEI) and the Toxic Release Inventory (TRI), developed by U.S.EPA, which provided 2014 mercury emission data by industrial sector and by state. Mercury emissions from WTE plants were calculated on the basis of 2012 individual plant stack tests, provided by all facilities operated by the two major WTE companies in the U.S., Covanta Energy and Wheelabrator Technologies. Mercury emissions from sanitary landfills were based on scientific studies, the known quantity of MSW landfilled, and the EPA record of total installed MW capacity of generating electricity from landfill gas.

The 2014 total anthropogenic emissions of mercury in the U.S. were 110,283 lb or 50,068 kilograms. The results of the analysis of emissions by industrial sector showed that the largest source of anthropogenic mercury were coal-fired pilot plants. Among industrial processes, the ferrous metals recycling and the cement industries were the largest emitters of mercury. The total of the mercury emissions of all U.S. WTE plants was estimated at 353 kilograms (770 lb), corresponding to 0.73% of the U.S. total. This number was nearly half of that reported by NEI for "municipal waste combustion (726 kg, or 1,600 lb).

A 2002 Earth Engineering Center study had shown that the mercury emissions of the U.S. WTE industry decreased from 81,800 kg in 1989 to 2,200 kg in 2001. The present study showed that between 2001 and 2014 the U.S. WTE industry mercury emissions were reduced further, by a factor of seven, to 363 kilograms (799 lb). Therefore, in comparison to 1989, the WTE Hg emissions had decreased by 99.6%.

In 2014, the electricity generated by the U.S. WTE industry was about 14.8 million MWh. Dividing the mercury emissions (363 kilograms) by this amount resulted to an average mercury emission of 0.024 g/MWh. This number compared with the average of 0.016 g/MWh estimate for coal-fired power plants. The annual mercury emissions from U.S. landfills in 2014 were estimated at 1,444 lb., i.e., 1.31% of the U.S. total mercury emissions. On the basis that the EPA Landfill Gas program (LMOP) reported the total landfill gas (LFG) generating capacity to be 2,394 MW of electricity, and assuming an overall 80% operating time of these installations, their average mercury emission was estimated at 0.039 g/MWh.

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1. Introduction

The purpose of this study was to compare the 2014 mercury emissions to the atmosphere from all U.S. anthropogenic sources. Sources of particular interest were mercury emissions associated with the management of post-recycling municipal solid waste (MSW), i.e. waste to energy (WTE) plants and sanitary landfills.

The mercury emissions data were obtained from the National Emissions Inventory (NEI) and the Toxic Release Inventory (TRI) developed by U.S. EPA, which analyzed the 2014 mercury emissions by industrial sectors and by state. The mercury emissions from WTE plants were calculated using the results of 2014 stack tests recorded and provided by all facilities operated by Covanta Energy and Wheelabrator Technologies..

The report is based on a detailed analysis of data of several documents and published public technical reports, using industrial ecology methodology.

2. Trends of total mercury emission in the U.S.

The objective of this study was to collect mercury emissions to the atmosphere from all waste-to-energy (WTE) plants in the U.S. and compare their collective emissions in the period 2014-2015 to all other sources of mercury emissions to the atmosphere. EPA currently tracks air emissions from large stationary sources under four main programs. Two of these programs are selected to be used as data sources for this paper, the National Emissions Inventory (NEI) and the Toxic Release Inventory (TRI).

The NEI database is built from air emissions data stored in the Emissions Inventory System (EIS) database. EIS contains information on stationary and mobile sources that emit criteria air pollutants and their precursors, as well as hazardous air pollutants. The NEI is prepared every three years by the EPA based primarily upon emission estimates and emission model inputs provided by state, local, and tribal air agencies for sources in their jurisdictions, and supplemented by data developed by the EPA. The Air Pollutant Report includes facility-level data from each of the year-specific NEIs (e.g., 2005, 2008, 2011, etc.) and does not include emissions from EIS for the years between the releases. From the most recent NEI, nearly 100,000 facilities are included in the Air Pollutant Report.

The TRI database tracks the management of over 650 toxic chemicals that may pose a threat to human health and the environment. Facilities that manufacture, process or otherwise use these chemicals in amounts above established levels must submit annual TRI reports on each chemical. More than 20,000 U.S. industrial facilities annually report to the EPA the quantities of TRI chemicals released to the environment or managed through recycling, energy recovery, and treatment. [1] This

[1] https://echo.epa.gov/help/reports/air-pollutant-report-help
[2] TRI National Analysis Supporting Tables, http://www.epa.gov/sites/production/files/2015-06/documents/factors_to_consider_6.15.15_final.pdf.

TRI data of On-site air releases of mercury and mercury comlbs includes fugitive or non-point air emissions, stack or point air emissions.

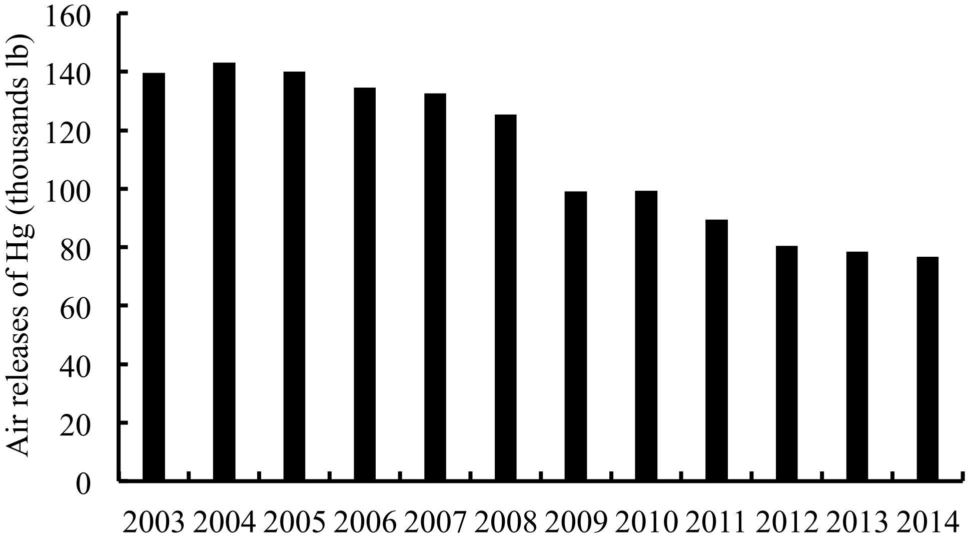

Figure 1. On-site Air Releases of Mercury and Mercury Comlbs, 2003-2014[2]

For the total mercury air emission in 2014, the TRI dataset is included in the NEI dataset and counted for 9.1% of the total mercury air emission in weight.

The burning of municipal and medical waste was once a major source of mercury emissions. The Clean Air Act was established in 1975 but it did not provide very strict rules regarding mercury emission. One of the goals of the 1975 Act was to set and achieve NAAQS (National Ambient Air Quality Standards) in every state, in order to reduce the public health risks posed by certain widespread air pollutants. However, the Clean Air Act required that EPA take several steps before regulating air toxics emissions, such as mercury, from power plants.

In November 1990, the Clean Air Act was revised by Congress and signed into law by President George H. W. Bush. Its amendments were designed to curb four major threats to the environment and to public health: acid rain, urban air pollution, toxic air emissions including mercury, and stratospheric ozone depletion. The 1990 Clean Air Act Amendments required the issuing of federal technology-based standards for major sources and for certain area sources. Section 112 required that EPA establish emission standards for major sources that would result to the maximum possible degree of reduction in emissions of hazardous air pollutants. These standards are referred to as "maximum achievable control technology" or "MACT" standards.

As a result of the MACT regulation, From the year of 2003 to 2014, the air release of

[2] TRI National Analysis Supporting Tables, http://www.epa.gov/sites/production/files/2015-06/documents/factors_to_consider_6.15.15_final.pdf.

mercury in the U.S. decreased by 45%. The most efficient way to remove mercury from the combustion gases is by means of dry scrubbing, followed by activated carbon injection and a fabric filter baghouse. [3]

The Hg sectors primarily focus on regulatory categories and categories of interest to the international community. This table shows the 2014 NEI mercury emissions for the key categories of interest in comparison to 1990. Also shown are the previous 2 triennial NEI years along with the most recent 2005 emissions, which were used in support of the MATS rule.[4]

Table 1. Trends in NEI mercury emissions – 1990, 2005, 2008 v3, 2011 v2 and 2014 NEI[5]

Source Category	1990 (tpy) Baseline for HAPs*, 11/14/2005	2005 (tpy) MATS** proposal 3/15/2011	2008 (tpy) 2008 v3	2011 (tpy) 2011 v2	2014 (tpy) 2014 v1	2014 emissions as % of U.S. total
Utility Coal Boilers (Electricity Generation Units – EGUs, combusting coal)	58.8	52.2	29.4	26.8	22.9	41.54%
Hospital/Medical/ Infectious Waste Incineration	51	0.2	0.1	0.1	0.02	0.04%
Municipal Waste Combustors	57.2	2.3	1.3	1	0.8	1.45%
Industrial, Commercial/Institutional Boilers and Process Heaters	14.4	6.4	4.2	3.6	3.1	5.62%
Mercury Cell Chlor-Alkali Plants	10	3.1	1.3	0.5	0.1	0.18%
Electric Arc Furnaces	7.5	7	4.8	5.4	4.5	8.16%
Commercial/Industrial Sold Waste Incineration	Not available	1.1	0.02	0.01	0.01	0.02%
Hazardous Waste Incineration	6.6	3.2	1.3	0.7	0.8	1.45%
Portland Cement Non-Hazardous Waste	5	7.5	4.2	2.9	3.2	5.80%
Gold Mining	4.4	2.5	1.7	0.8	0.3	0.54%
Sewage Sludge Incineration	2	0.3	0.3	0.3	0.3	0.54%
Mobile Sources	Not available	1.2	1.8	1.3	1.2	2.18%
Other Categories	29.5	18	10.7	13	17.9	32.47%
Total (all categories)	246	105	61	56	55.0	100.00%

*: Hazardous Air Pollutants (HAPs)

**: Mercury and Air Toxics Standards (MATS)

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3 Hensman, Carl E. H. ighly Efficient Removal of Mercury From Industrial Flue Gas, Small Business Innovation Research (SBIR) - Phase I (2004)

4 2014 National Emissions Inventory, version 1, Technical Support Document

5 ibid

It should be noted that in 1990, coal-fired boilers in electricity generation (58.8 tons), hospital/medical/infectious waste incineration (51 tons), and municipal waste combustors (57.2 tons) were the major anthropogenic sources of mercury emission to the atmosphere. Table 1 shows that by 2014, mercury emissions from hospital/medical/infectious had dropped to 0.02 tons and from municipal waste combustors (WTE plants) to 0.8 tons. However, as will be shown in a later section of this report, this study showed that WTE emissions in 2014 were even lower, at less than 0.4 tons. In the period 1990-2014, the total anthropogenic mercury emission in the U.S. decreased by 77.6%, mercury emissions from utility coal boilers by 61.1%, and from hospital/medical/infectious and, as will be shown in a later section of this report, WTE by over 99%.

3. Analysis by industrial sectors and regions in 2014

In the NEI 2014 database, the total mercury emissions were 110,283 lb (Table 2). The categories contributing more than 7,000 lb of mercury emission were coal-fired power plants, the ferrous metal recycling industry, oil combustion in industrial boilers and non-vehicular ICEs, waste disposal, and cement production.

Table 2. U.S. 2014 mercury emissions by industrial sector

Sector	Mercury emission. lb	Emission as % of total U.S.
Fuel Comb - Electric Generation - Coal Total	45,676	41.42%
Industrial Processes - Ferrous Metals Total	11,095	10.06%
Fuel Comb - Industrial Boilers, ICEs - Oil Total	8,161	7.40%
Waste Disposal Total	7,581	6.87%
Industrial Processes - Cement Manuf Total	7,384	6.70%
Industrial Processes - NEC Total	4,603	4.17%
Miscellaneous Non-Industrial NEC Total	4,114	3.73%
Industrial Processes - Non-ferrous Metals Total	2,682	2.43%
Industrial Processes - Chemical Manuf Total	2,082	1.89%
Fuel Comb - Electric Generation - Natural Gas Total	1,921	1.74%
Fuel Comb - Industrial Boilers, ICEs - Coal Total	1,737	1.58%
Fuel Comb - Residential - Oil Total	1,521	1.38%

Fuel Comb - Industrial Boilers, ICEs - Natural Gas Total	1,516	1.37%
Mobile - Locomotives Total	1,506	1.37%
Industrial Processes - Petroleum Refineries Total	1,206	1.09%
Fuel Comb - Comm/Institutional - Oil Total	1,027	0.93%
Fuel Comb - Electric Generation - Other Total	924	0.84%
Industrial Processes - Storage and Transfer Total	755	0.68%
Mobile - On-Road non-Diesel Light Duty Vehicles Total	673	0.61%
Fuel Comb - Industrial Boilers, ICEs - Biomass Total	663	0.60%
Industrial Processes - Mining Total	531	0.48%
Fuel Comb - Industrial Boilers, ICEs - Other Total	462	0.42%
Industrial Processes - Oil & Gas Production Total	428	0.39%
Industrial Processes - Pulp & Paper Total	369	0.33%
Solvent - Industrial Surface Coating & Solvent Use Total	288	0.26%
Fuel Comb – Commerc. /Institutional - Coal Total	256	0.23%
Fuel Comb – Commerc./Institutional - Natural Gas Total	186	0.17%
Fuel Comb - Electric Generation - Biomass Total	171	0.16%
Fuel Comb - Electric Generation - Oil Total	137	0.12%
Fuel Comb - Residential - Wood Total	127	0.11%
Fuel Comb - Residential - Natural Gas Total	115	0.10%
Agriculture - Livestock Waste Total	96	0.09%
Mobile - Non-Road Equipment - Diesel Total	75	0.07%

Fires - Agricultural Field Burning Total	40	0.04%
Fuel Comb - Comm/Institutional - Biomass Total	36	0.03%
Mobile - On-Road Diesel Heavy Duty Vehicles Total	34	0.03%
Mobile - Non-Road Equipment - Gasoline Total	33	0.03%
Mobile - Commercial Marine Vessels Total	31	0.03%
Mobile - On-Road Diesel Light Duty Vehicles Total	17	0.02%
Mobile - Non-Road Equipment - Other Total	7.6	0.01%
Mobile - On-Road non-Diesel Heavy Duty Vehicles Total	7.0	0.01%
Solvent - Consumer & Commercial Solvent Use Total	4.7	0.00%
Fuel Comb - Residential - Other Total	1.8	0.00%
Fuel Comb - Comm/Institutional - Other Total	0.8	0.00%
Grand Total	110,283	100.00%

* *The category "waste disposal" includes: open burning – brush, residential household waste, land clearing debris; switches and relays; landfills; thermostats; thermometers; publicly owned treatment works; municipal waste combustors.*

4. Emissions of mercury by state

As shown in Table 3, Texas emitted the most mercury, nearly twice as much as the second large emitter, Pennsylvania, Ohio, and California were the next largest emitters of mercury.

Table 3. Mercury emissions by the fifty states in 2014

State	Hg emission lb.	Hg emission, % of total U.S.	State	Hg emission lb.	Hg emission, % of total U.S.
TX	13,582	12.32%	**NV**	1,464	1.33%
PA	7,952	7.21%	**WI**	1,355	1.23%
OH	5,523	5.01%	**VA**	1,317	1.19%
CA	5,246	4.76%	**GA**	1,308	1.19%
AL	4,989	4.52%	**MS**	1,173	1.06%
IN	4,299	3.90%	**UT**	1,163	1.05%
MI	3,819	3.46%	**NJ**	1,066	0.97%
MO	3,630	3.29%	**ID**	1,031	0.94%
IL	3,372	3.06%	**WA**	1,010	0.92%
FL	3,135	2.84%	**MA**	661	0.60%
AR	3,074	2.79%	**MD**	654	0.59%
NY	2,992	2.71%	**CT**	551	0.50%
MN	2,459	2.23%	**OR**	511	0.46%
WV	2,434	2.21%	**AK**	450	0.41%
KY	2,413	2.19%	**MT**	394	0.36%
ND	2,320	2.10%	**NM**	283	0.26%
AZ	2,315	2.10%	**RI**	264	0.24%
IA	2,275	2.06%	**DE**	263	0.24%
WY	2,254	2.04%	**PR**	250	0.23%
NC	2,090	1.90%	**ME**	244	0.22%
SC	1,991	1.81%	**SD**	220	0.20%
LA	1,891	1.71%	**VT**	119	0.11%
OK	1,825	1.65%	**HI**	88	0.08%
TN	1,795	1.63%	**DC**	25	0.02%

KS	1,771	1.61%	**DM**	17	0.02%
NE	1,667	1.51%	**All other**	238	0.22%
NH	1,557	1.41%			
CO	1,496	1.36%	**Total**	110283	100.00%

The states with highest emissions were Texas, Pennsylvania, Ohio, California, and Alabama, Indiana, Michigan, Missouri, Illinois, Florida, Arkansas, New York, Minnesota, West Virginia, and Kentucky.

Table 4, shows the 2014 distribution of mercury emissions among various industrial sectors in Texas. Next to coal-fired utilities (8,950 lb or 65.9% of Texas total), other major sources of mercury emissions were the ferrous (1,391) and non-ferrous (657 lb) metal industries, petroleum refineries (393 lb), and cement production (320 lb; Table 4).

Table 4. 2014 major anthropogenic mercury emission sources in Texas

Sector	Mercury (lb)	% of state total
Fuel Comb - Electric Generation - Coal Total	8950	66%
Industrial Processes - Ferrous Metals Total	1391	10%
Industrial Processes - Non-ferrous Metals Total	657	5%
Waste Disposal Total*	535	4%
Industrial Processes - Petroleum Refineries Total	393	3%
Industrial Processes - Cement Production Total	320	2%
Fuel Comb - Industrial Boilers, ICEs - Natural Gas Total	249	2%
Miscellaneous Non-Industrial NEC Total	220	2%
Industrial Processes - Storage and Transfer Total	148	1%
Industrial Processes - Oil & Gas Production Total	138	1%

* *Waste disposal-See note under Table 1*

Emissions of mercury from cola fired plants was highest in Texas, nearly three times as high as the second emitter Ohio. Pennsylvania, North Dakota, Michigan and Missouri are also big emitters in electricity generation sector. In the commercial/institutional fuel combustion sector, Pennsylvania, New York, Iowa, New Jersey, and Ohio were the top emitters. In the residential fuel combustion sector, New York state ranked as the first place, and is 1.7 times as the second emitter Pennsylvania, following big emitters are Massachusetts, Connecticut, and Maine. In the waste disposal sector, the top emitters are New York, California, Texas, Pennsylvania, and Ohio. Industrial boilers and ICEs sector has top emitters as Pennsylvania, New Hampshire, New York, West Virginia and Arkansas.

In Pennsylvania, cola-fired electricity generation constituted 30.8% of the total mercury emission. The oil combustion in industrial boilers and ICEs composed 30.5% of the total emission, other big sources are NEC (not elsewhere classified) industries, waste disposal, and commercial/institutional oil combustion.

Table 5. 2014 mercury emission from various industrial sectors in Pennsylvania

Sector	Mercury (lb)	% of state total
Fuel Comb - Electric Generation – Coal Total	2450	31%
Fuel Comb - Industrial Boilers, ICEs - Oil Total	2424	30%
Industrial Processes - NEC Total	772	10%
Waste Disposal Total*	454	6%
Fuel Comb - Comm/Institutional - Oil Total	301	4%
Industrial Processes - Ferrous Metals Total	252	3%
Fuel Comb - Residential - Oil Total	247	3%
Industrial Processes - Cement Manuf Total	236	3%
Miscellaneous Non-Industrial NEC Total	174	2%
Industrial Processes - Non-ferrous Metals Total	165	2%

* *Waste disposal-See note under Table 1*

In Ohio, electricity generation composed 33.7% of the total emission, natural gas combustion for electricity generation also counted for 20.5% of the total emission. Other big sources are ferrous metal, waste disposal, and cement manufacturing.
Add % Column

Table 6. 2014 Mercury emission from different industrial sectors in Ohio

* Waste disposal-See note under Table 1

Sector	Mercury (lb)	% of state total
Fuel Comb - Electric Generation - Coal Total	1859	34%
Fuel Comb - Electric Generation - Natural Gas Total	1134	21%
Industrial Processes - Ferrous Metals Total	710	13%
Waste Disposal Total*	441	8%
Industrial Processes - Cement Manuf Total	270	5%
Industrial Processes - NEC Total	264	5%
Industrial Processes - Non-ferrous Metals Total	161	3%
Fuel Comb - Industrial Boilers, ICEs - Natural Gas Total	113	2%
Miscellaneous Non-Industrial NEC Total	104	2%
Fuel Comb - Industrial Boilers, ICEs - Coal Total	101	2%

For specific industries, the highest petroleum industry emission was in Texas, which was twice as large as the second emitter California. Ohio, North Dakota and Oklahoma are also big contributors in the petroleum sector. In the ferrous metals industry, Indiana, Alabama, Minnesota are the top three emitters and accounted for 43.3% of emission of the whole sector. South Carolina and Ohio are also big contributors in the ferrous metals industry emission. In the non-ferrous metals industry, Texas, Nevada, North Carolina, Arizona and Illinois accounted for 71.2% of the total emission from the sector. In the chemical manufacturing sector, Idaho, South Carolina and North Carolina composed 60% of the total emission, Louisiana and West Virginia also contributed 11%.

The cement industry in California accounted for 29.2% of the total emission, Missouri, Florida, Alabama, and Indiana accounted for 31.6%. As for the mobile sources, California is the biggest emitter, followed by Texas, Nebraska, Illinois and Ohio.

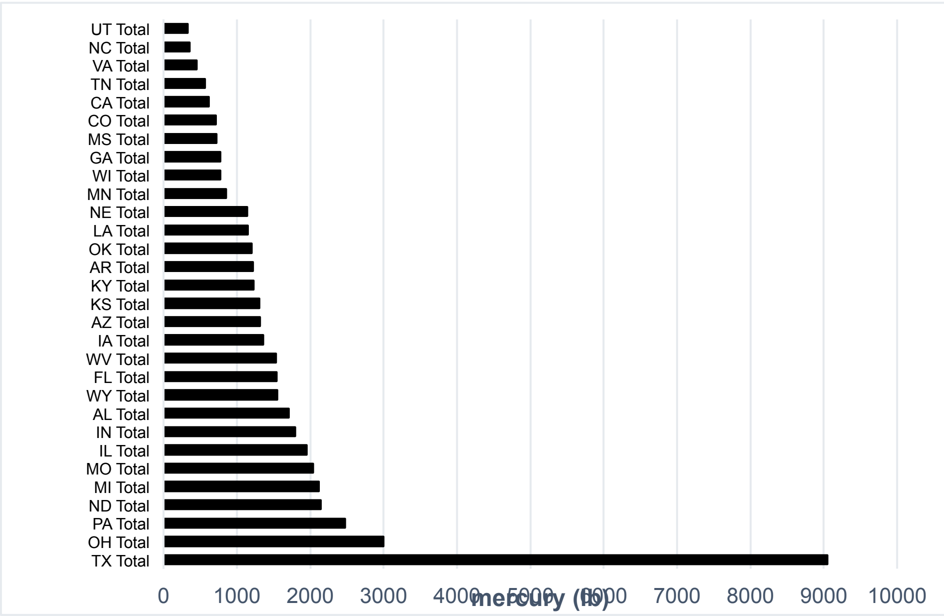

Figure 2. 2014 state contribution to mercury emission in electricity generation

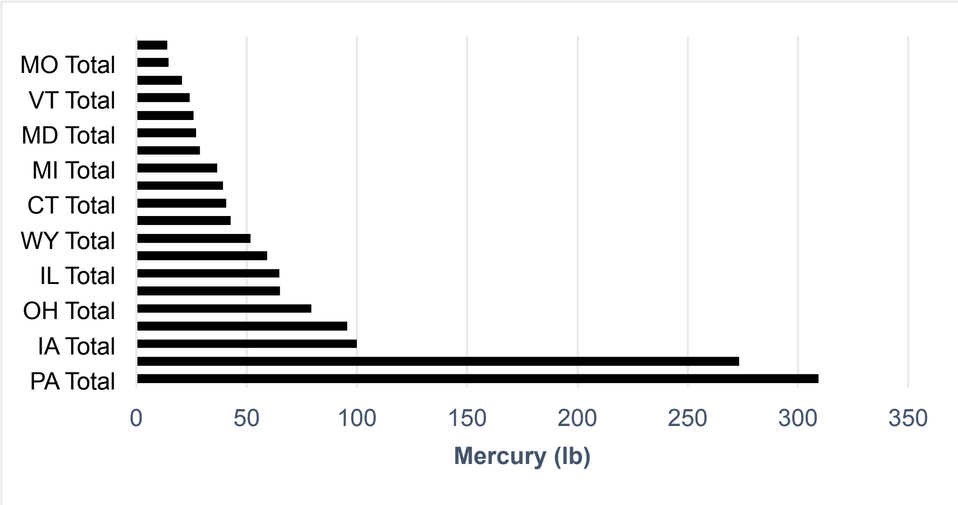

Figure 3. 2014 state contribution to mercury emission in commercial/institutional

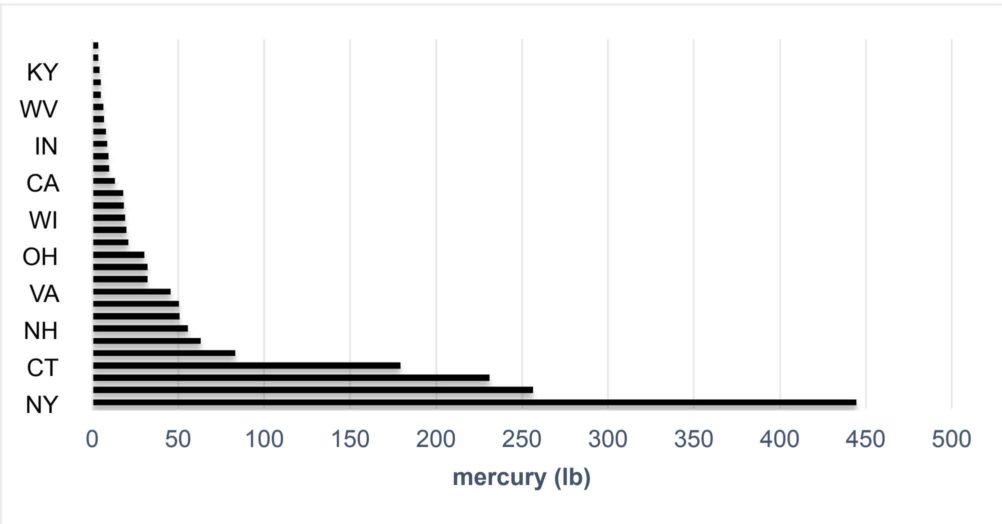

Figure 4. 2014 state contribution to mercury emission in residential

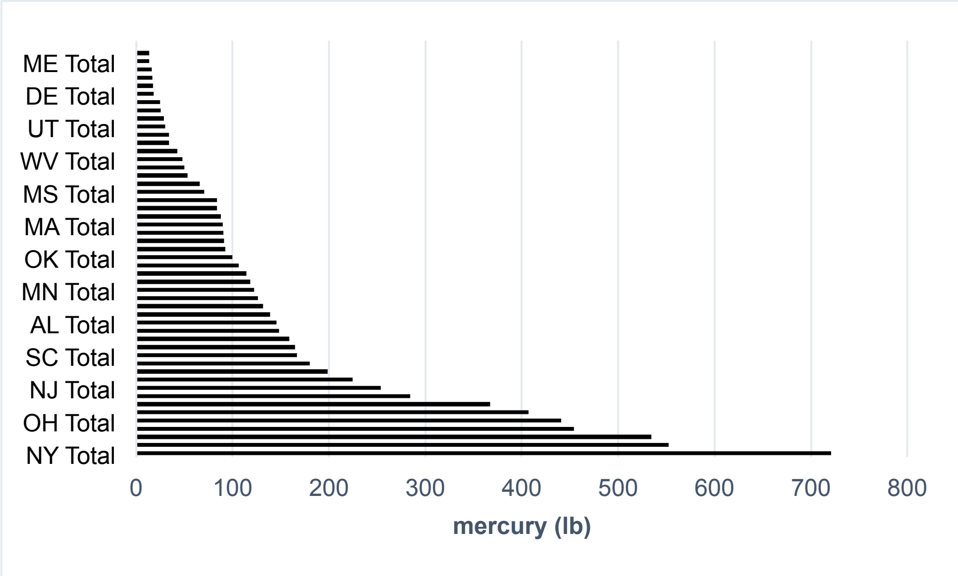

Figure 5. 2014 state contribution to mercury emission in waste disposal

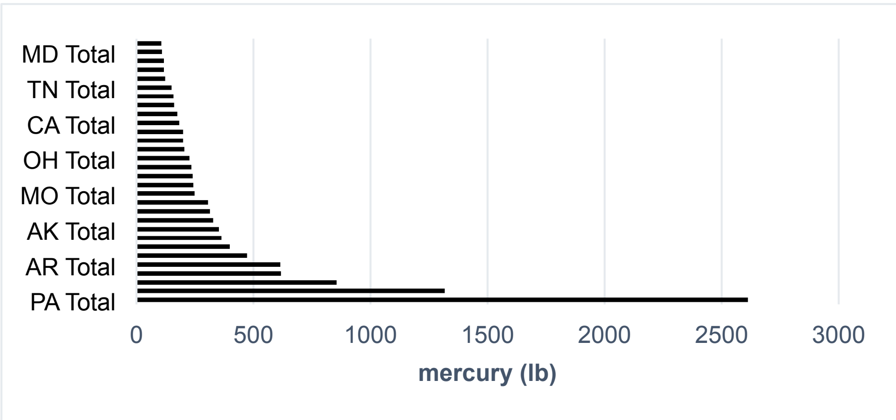

Figure 6. 2014 state contribution to mercury emission in industrial boilers, ICEs

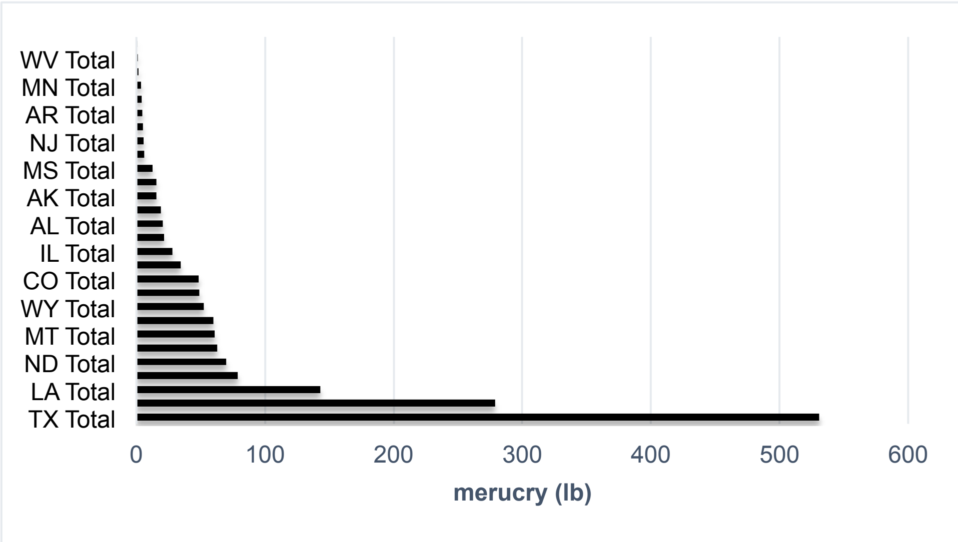

Figure 7. 2014 state contribution to mercury emission in petroleum refinery

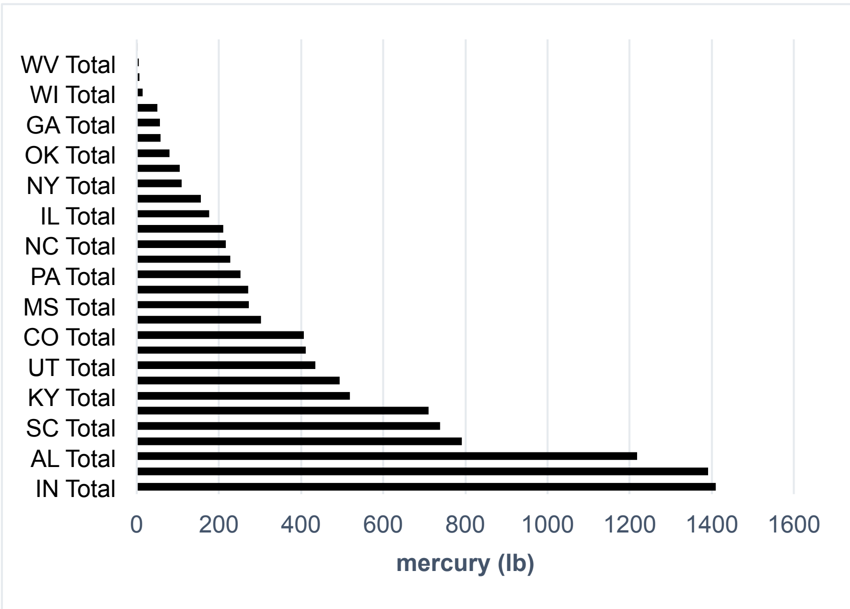

Figure 8. 2014 state contribution to mercury emission in ferrous metals industry

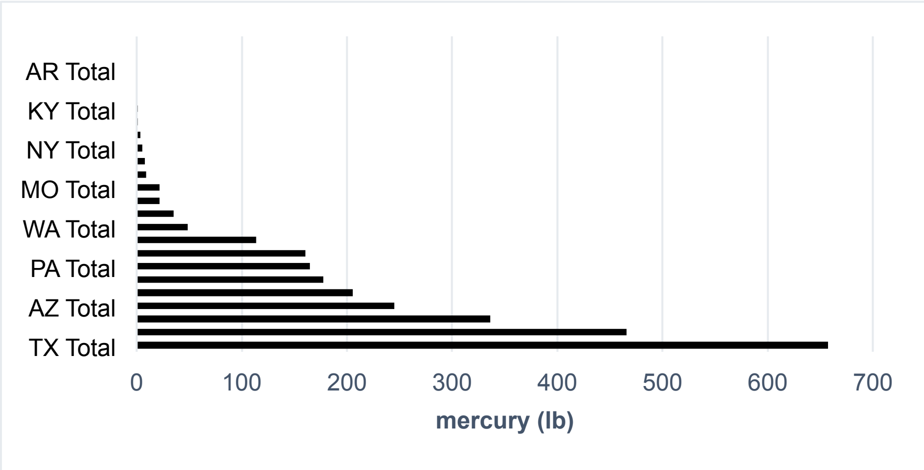

Figure 9. 2014 state contribution to mercury emission in non-ferrous metals industry

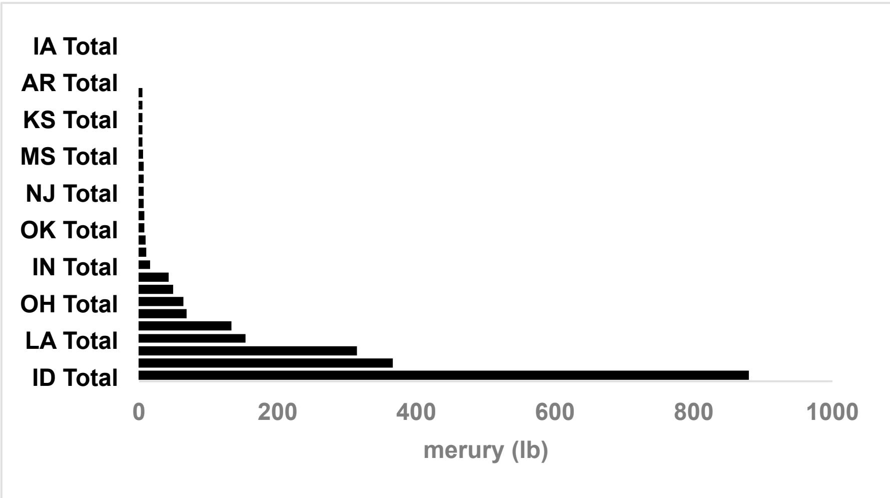

Figure 10. 2014 state contribution to mercury emission in chemical manufacturing

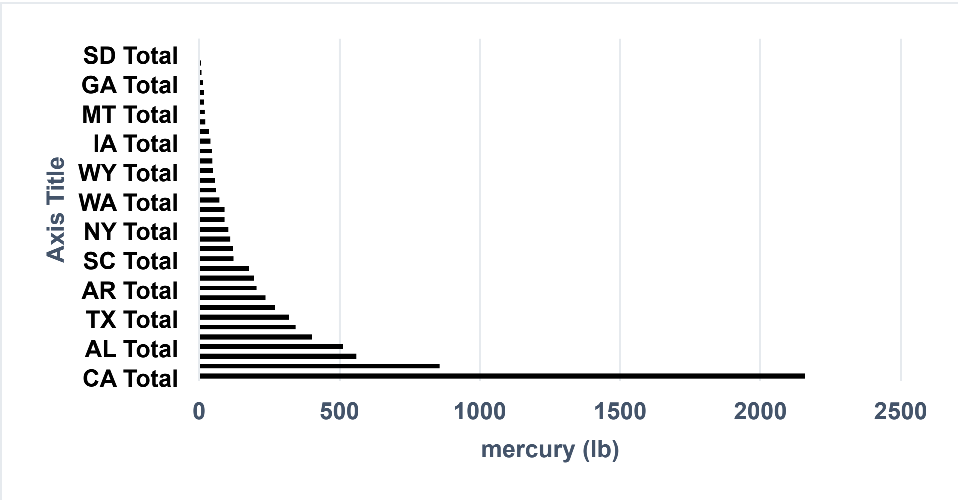

Figure 11. 2014 state contribution to mercury emission in cement manufacturing

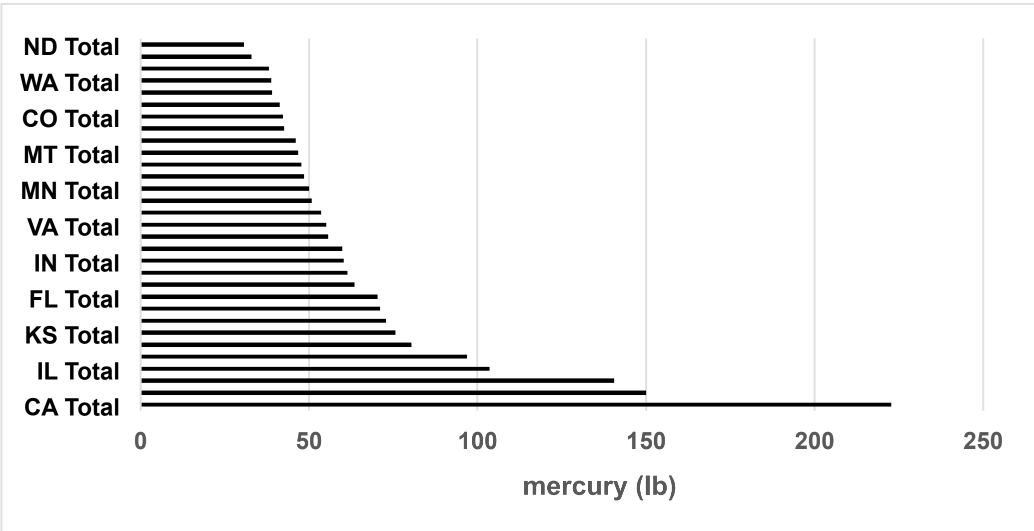

Figure 12. 2014 state contribution to mercury emission in mobile sources

Pennsylvania and New York have very high commercial/ institutional emissions. New York is also the biggest residential contributor; other big contributors of residential emissions are Pennsylvania, Massachusetts, Connecticut, Maine, and New Jersey. This can due to the cold weather in the winter and thus the fossil fuel combustion for heating. However, the top 10 emitters of waste disposal except for Arkansas and New Jersey (ranked as 11th in 2017) are ranked among the top 10 populated states. Pennsylvania has significant high emissions in industrial boilers and ICEs. This is followed by New Hampshire and New York. Petroleum refinery industry emissions is leaded by Texas, and ferrous-metal industry emissions is leaded by Indiana, Texas and Alabama. Indiana is also ranked first in chemical manufacturing emissions.

California contributed the most in cement manufacturing, mobile sources emissions, and more than 90% of the emissions of the solvent industry.

4. Waste to energy (WTE) mercury emissions in 2014

According to the U.S. EPA, Americans generated about 250 million tons of trash of which 53.7% (134 million tons) were landfilled, 11.7% (29.3 million tons) were combusted in waste to energy (WTE) plants, and the rest were either recycled or composted. Combustion with energy recovery includes combustion of MSW, in mass burn or refuse-derived fuel form, and combustion with energy recovery of source separated materials in MSW (e.g., wood pallets, tire-derived fuel).[6]

However, according to the Columbia-BioCycle bi-annual surveys of waste generation and disposition in the U.S.,[7] the amount of MSW generated in the U.S. is grossly understated by EPA. Figure 13 below shows that the actual total MSW generated in the U.S. in 2011 was about 390 million tons. The main difference with the EPA number is that the actual total landfilling, as reported by the fifty states to the Columbia survey was 254 million tons, i.e., about 120 million tons greater than that reported by EPA.

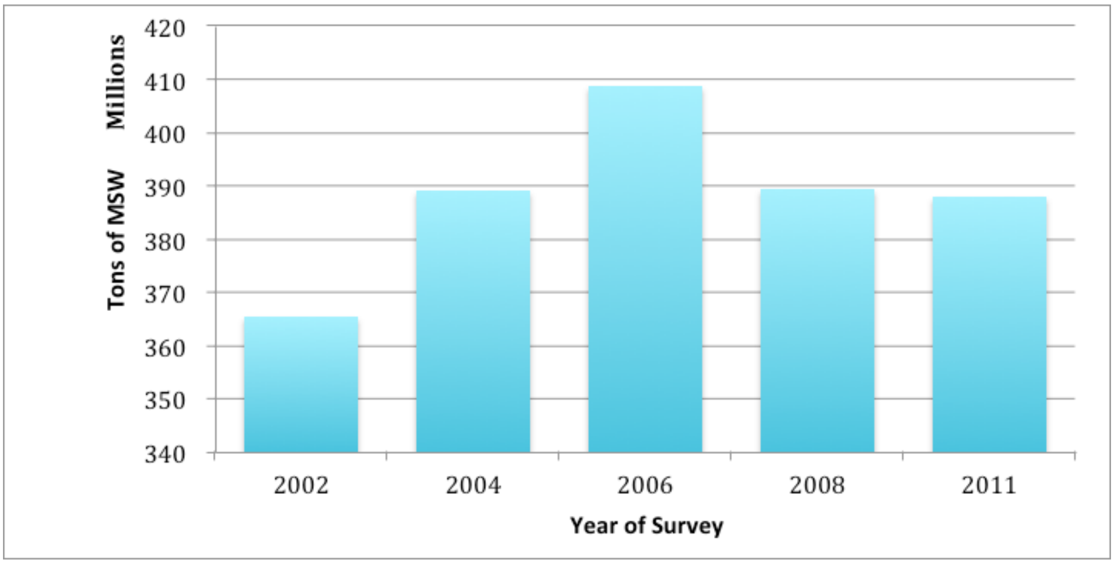

Figure 13. Annual MSW generation in the U.S.(Columbia-BioCycle surveys)

[6] Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2011. U.S. EPA

[7] Dolly Shin, Generation and Disposition of Municipal Solid Waste (MSW)in the United States –A National Survey. http://www.seas.columbia.edu/earth/wtert/sofos/Dolly_Shin_Thesis.pdf

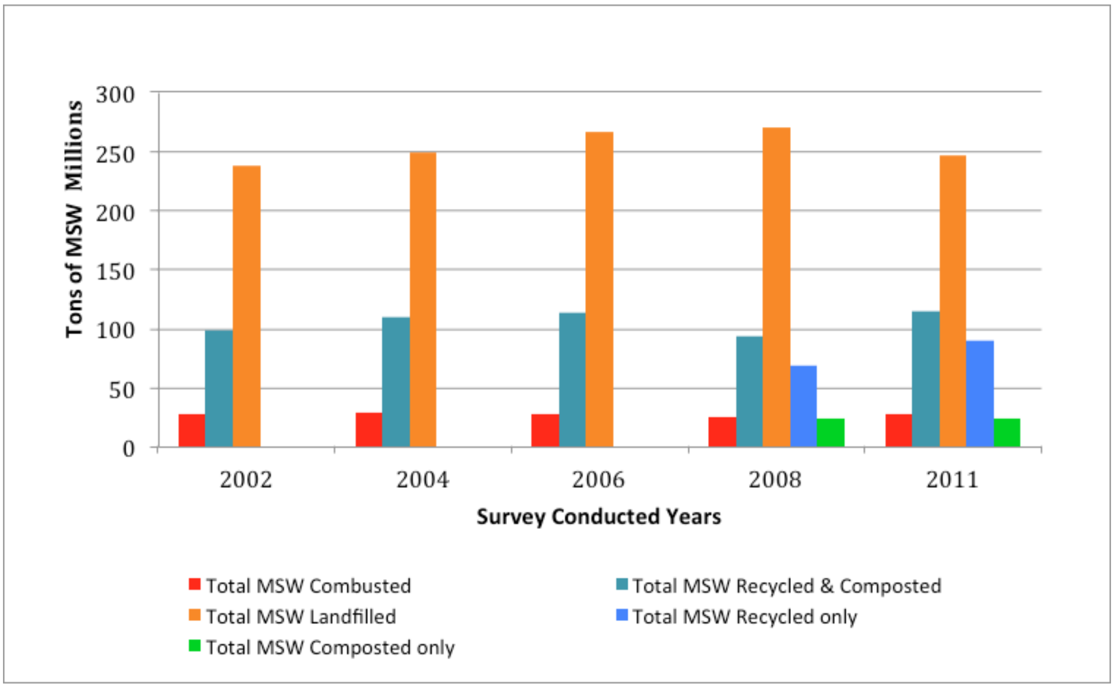

Figure 14. 2002-2011 MSW disposal

Currently there are 77 operating WTE facilities in the United States. These facilities are located in 25 states, mainly in the northeast; in 2014, this number was 84 in 2014 and produced 14.8 million MWh of power by combusting 29.7 million tons of MSW (average supply of electricity by U.S. WTE plants to the grid: 0.5 MWh/ton MSW).

The current WTE infrastructure dates from before 1996: 65% of the capacity was built in the 1980s, and last 35% between 1990 and 1996. Though some plants have shut down, some have increased their capacity by adding boilers.[8] There are still more than 50% of MSW were disposed through landfill and other disposal.

[8] Michaels, Ted. 2014. The 2014 ERC Directory of Waste-To-Energy Facilities. Energy Recovery Council. http://energyrecoverycouncil.org/wp-content/uploads/2016/06/ERC-2016-directory.pdf

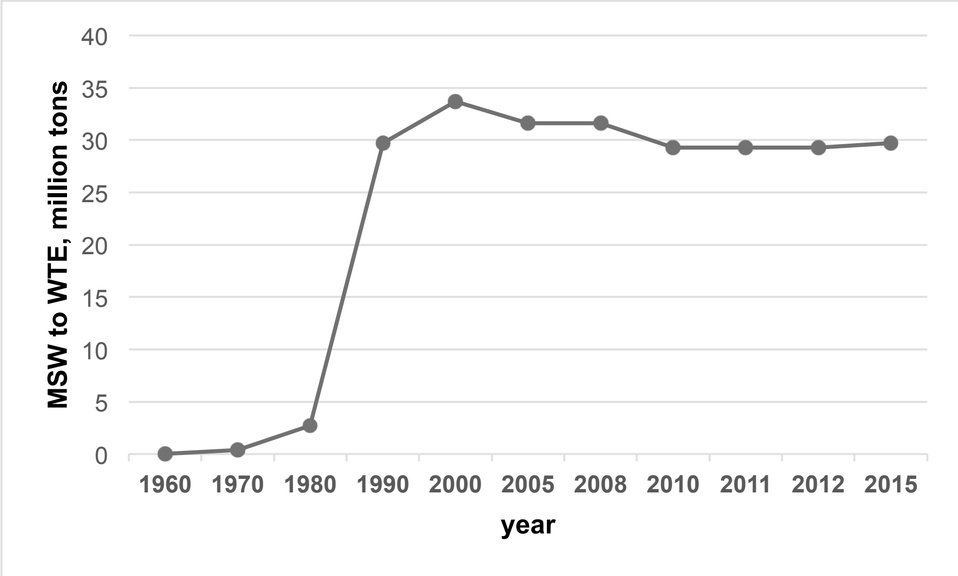

Figure 15. Tons of U.S. MSW to combustion with energy recovery (WTE)

Using the EPA method, the annual mercury emission by WTE in the years 2014-2015 is estimated to be 363 kg/year. Using the simplified method of the Earth Engineering Center (EEC) of Columbia University, the total mercury emission by WTE in on an average level of the years 2014-2015 was calculated to be 353 kg/year.

Mercury emissions from WTE plants were calculated using 2014 stack tests recorded and provided by all facilities operated by Covanta Energy and Wheelabrator Technologies[9], which combined represent 85.8% of the WTE capacity in the USA. The remaining 14.2% of the U.S. WTE capacity was assumed to have the same average emissions.

The methodology of the EPA method is described as following. Measured stack exhaust concentrations are converted to annual mass emissions based on an EPA volume of combustion components per unit of heat content factor (F-Factor) of 9570 dscf at 0% O_2 /MMBtu[10], assuming an average MSW heat content of 5,000 Btu /lb,

$$M_{iTEQ} = C_{iTEQ} \times F_d \times \frac{20.9}{20.9-7} \times HHV_{MSW} \times \frac{1}{35.3} \times W,$$

Where, M= mass emissions(μ g)

C= stack concentration(μ g/dscm)

F_d= volume of combustion components per unit of heat content factor (9570 scf at 0%O_2 /million Btu)

HHV_{MSW}= higher heating value of MSW (10 million Btu /short ton)

35.3= dry standard cubic feet per dry standard cubic meter (dscm)

W= mass of waste combusted at facility.

In contrast, the EEC method directly consider the stack exhaust flue gas to be 4,000

[9] Reference source needed

[10] Title 40 Protection of Environment, Code of Federal Regulations, 60 Appendix A, Method 19, Table 19-2

Nm^3 /ton of MSW, then uses the measured stack exhaust concentratios to calculate the mercury emission per ton MSW; and finally multiplies by the annual tons of MSW processed in the WTE facility to calculate kg Hg per year..

Table 7. Annual mercury emission from WTE facilities, 2014-2015*

Facility #	MSW Processed (tons)	Hg , kg/year, using EPA method	Hg, kg/year using simplified EEC method	Hg, lb/year, EPA method	Hg emission per ton of MSW processed, ppm)
1	728,246	2.99	2.94	6.59	0.034
2	759,011	1.37	1.34	3.02	0.021
3	514,230	2.28	2.24	5.02	0.019
4	191,490	1.67	1.64	3.68	0.012
5	149,614	9.72	9.54	21.41	0.048
6	189,730	19.13	18.78	42.14	0.015
7	304,747	26.19	25.7	57.69	0.004
8	487,354	8.91	8.74	19.63	0.005
9	463,152	0.98	0.96	2.16	0.007
10	440,715	2.62	2.57	5.77	0.009
11	730,255	7.67	7.53	16.89	0.007
12	695,663	2.77	2.72	6.10	0.006
13	192,955	9.6	9.42	21.15	0.007
14	115,667	0.99	0.98	2.18	0.009
15	691,755	23.84	23.4	52.51	0.038
16	349,716	1.86	1.82	4.10	0.009
17	230,304	1.31	1.29	2.89	0.007
18	213,387	1.71	1.68	3.77	0.012
19	297,519	0.61	0.6	1.34	0.006
20	381,126	0.16	0.15	0.35	0.028
21	1,217,652	0.78	0.76	1.72	0.017
22	890,901	3.79	3.72	8.35	0.032
23	926,145	3.59	3.52	7.91	0.011
24	283,752	7.98	7.84	17.58	0.004
25	602,060	1.2	1.18	2.64	0.005
26	1,033,957	17.89	17.56	39.41	0.008
27	331,433	1.99	1.95	4.38	0.009
28	571,529	0.82	0.8	1.81	0.019
29	267,699	1.41	1.39	3.11	0.004
30	326,777	12.31	12.08	27.11	0.08

31	334,921	1	0.98	2.20	0.006
32	189,127	2.1	2.06	4.63	0.008
33	764,861	1.2	1.18	2.64	0.002
34	178,434	6.14	6.03	13.52	0.004
35	158,093	3.26	3.2	7.18	0.001
36	403,420	0.64	0.63	1.41	0.002
37	615,430	1.9	1.86	4.19	0.007
38	456,466	1.51	1.49	3.33	0.009
39	171,885	1.07	1.05	2.36	0.051
40	182,769	0.88	0.87	1.94	0.007
41	601,276	3.18	3.12	7.00	0.033
42	777,982	24.37	21.9	53.68	0.003
43	322,072	15.52	13.41	34.19	0.003
44	338,029	9.74	11.83	21.45	0.005
45	786,488	2.28	7.4	5.02	0.017
46	82,030	7.16	22.11	15.77	0.013
47	416,062	2.85	6.58	6.28	0.006
48	258,747	1.18	1.6	2.60	0.005
49	1,070,156	2.62	2.13	5.77	0.006
50	806,487	3.37	1.99	7.42	0.004
51	129,715	4.1	1.61	9.03	0.005
52	274,378	4.89	1.15	10.77	0.008
53	330,199	4.18	0.81	9.21	0.005
54	548,006	1.25	0.67	2.75	0.002
55	164,235	0.98	5.77	2.16	0.006
56	430,593	25.89	6.38	57.03	0.008
Covanta + Wheelabrator facilities	25,370,402	311.4	302.65	685.90	0.013
All other WTE plants	4,199,598	51.55		113.54	0.013
All U.S. WTE plants	29,570,000	362.95		799.44	0.013

The Covanta Energy and Wheelabrator facilities who provided mercury emission data to this study represent 85.8% of the WTE capacity in the USA. In 2014, 29.57 million tons of MSW was processed in WTE. Table 8 shows the distribution of WTE emissions in the U.S.

Table 8. Distribution of U.S. WTE capacity among states

State	% of total U.S. WTE capacity	State	% of total U.S. WTE capacity
MD	13.31%	CA	1.82%
VA	11.79%	FL	1.48%
PA	11.62%	MA	1.02%
FL	10.46%	MN	0.92%
NJ	10.01%	IN	0.57%
NY	8.74%	OK	0.50%
HI	8.22%	AL	0.43%
CT	6.72%	OR	0.40%
MA	5.48%	NH	0.38%
BC	3.77%	MI	0.20%
NY	2.17%	total	100%

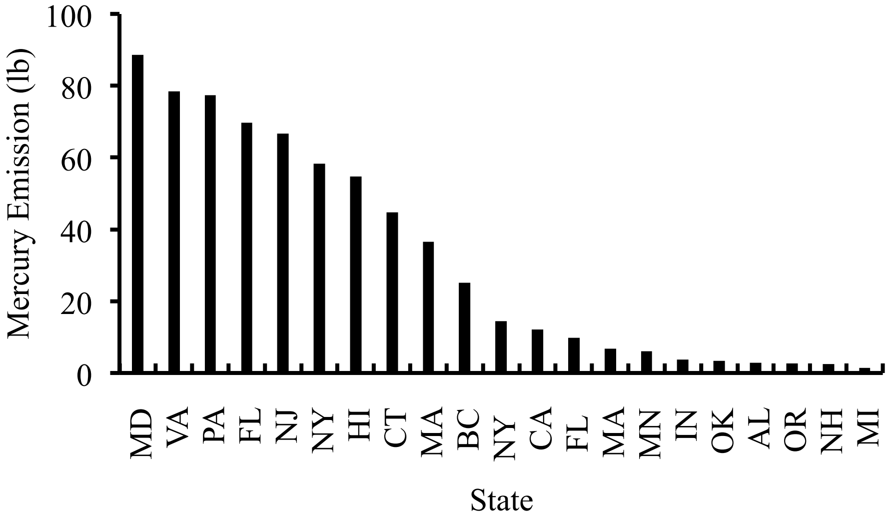

Figure 16. State contribution of WTE mercury emission

A 2002 Earth Engineering Center study had shown that the mercury emissions of the U.S. WTE industry decreased from 81,800 kg in 1989 to 2,200 kg in 2001. The present study showed that, between 2001 and 2014, the U.S. WTE industry mercury emissions were reduced further, by a factor of seven, to 363 kilograms (799 lb). Therefore, in comparison to 1989, the WTE Hg emissions decreased by 99.6%. The most significant factor was the introduction in the Air Pollution Control system of activated carbon injection and fabric filter baghouse. The second important factor was the success of the EPA program in phasing out the use of mercury. This has resulted in decreasing the mercury concentration in the MSW feedstock to WTE plants (15) from over 4 parts per million in the eighties to 0.4 ppm in 2016 (Figure 17, ref. 16).

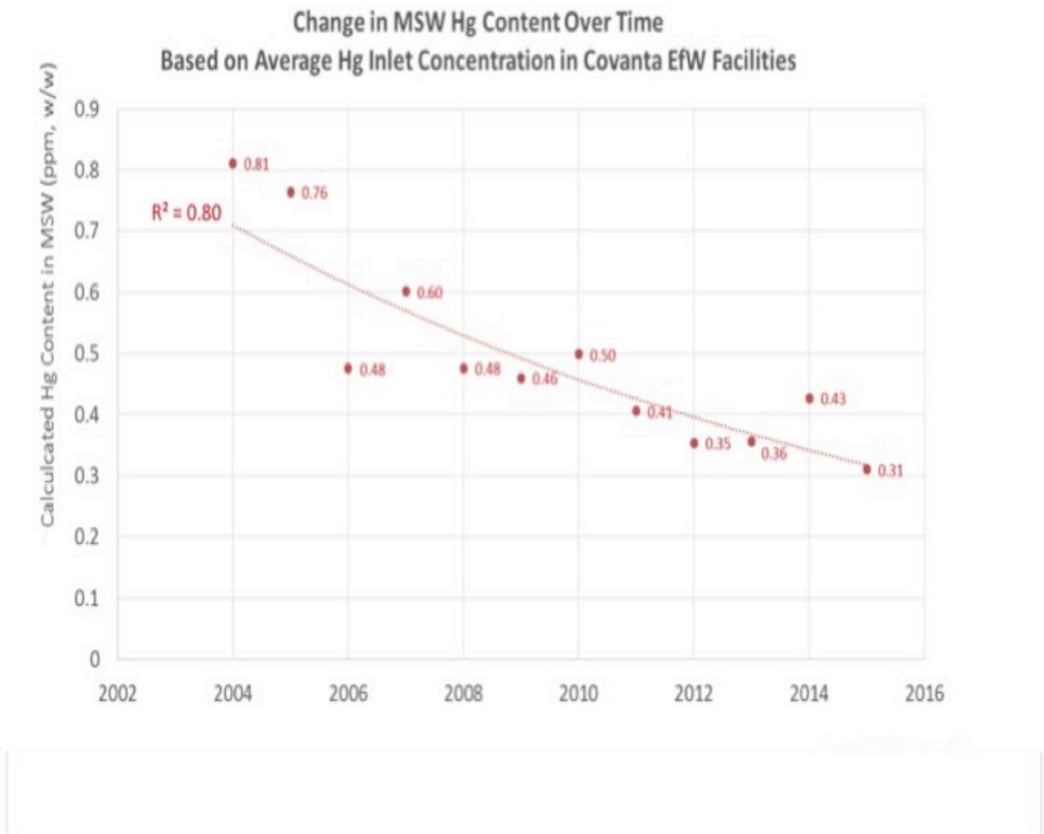

Figure 17. Average mercury concentration in MSW to Covanta Energy plants (16)

5. Estimate of landfill mercury emission

Earlier mercury emission factors for landfills (e.g., Themelis and Gregory, 2002) were based on measurements in landfill gas. However, Lindberg et al. (2005)[11], measured mercury emissions from the working face of four landfills in Florida and determined emission factors, per ton of waste placed in a landfill annually, that ranged from 1-6 mg per ton of waste. The average of these emission factors is 2.5 mg/ton of waste, or 5.51×10^{-6} lb/ton of MSW disposed in U.S. landfills.

As noted earlier, the Powell et al. study (2015), was in agreement with the earlier Columbia-BioCycle national surveys. The landfill disposal rate in the US in 2012 was reported to be 262 million U.S. tons[12]. Therefore by multiplying this rate of landfilling by the mercury emission factor of Lindberg et al (2005) resulted to the following estimate of mercury emissions from U.S. landfills in 2012: 1444 lb (654 kg).

According to the work by Kaplan et al., the electricity generated from 1 ton of MSW

[11] Steve E. Lindberg. Airborne Emissions of Mercury from Municipal Solid Waste. I: New Measurements from Six Operating Landfills in Florida. ISSN 1047-3289 J. Air & Waste Manage. Assoc. 55:859–869.

[12] Powell et al, Estimates of solid waste disposal rates and reduction targets for landfill gas emissions. DOI: 10.1038/NCLIMATE2804.

by LFGTE is 41-84 kWh/ton. [13] On this basis, the average mercury emission per unit electrical generation for sanitary landfilling is 0.045g/MWh. In the following section, an alternative method was used to estimate LFG electricity emission at 0.039 grams mercury per MWh produced.

6. Mercury emissions of different sources of electricity

WTE plants serve two purposes: Avoiding the use of land for landfilling and also generating electricity. However, it is interesting to compare their mercury emission, per MWh of electricity generated with coal-fired power plants.

As shown earlier, the U.S. WTE industry provides an annual 14.8 million MWh to the grid and emits a total of 363 kilograms of mercury. This amount corresponds to an average emission of 0.024 grams mercury per MWh of electricity to the grid.

According to EIA, the U.S. generation of electricity amounts to four billion MWh, 33% of which is produced by coal-fired utilities (1.32 billion MWh). Converting the 45,676 pounds of coal-fired plant emissions (Table 1) to grams and dividing by 1.32 billion MWh results in the estimate of 0.016 grams per MWh of coal-fired power.

Electricity is also produced by capturing and using landfill gas (LFG) at sanitary landfills. As noted earlier, the mercury emission from U.S. landfills in 2014 was estimated at 1,444 lb., i.e., 1.31% of the U.S. total mercury emissions. The EPA landfill gas collection program (LMOP) reported the total landfill gas (LFG) generating capacity to be 2,394 MW of electricity. Assuming an average operating time of these installations of 80% during a year, results in the estimate of average mercury emission of 0.039 g/MWh.

7. **Conclusions**

The results of sector analysis showed that the biggest anthropogenic 2014 mercury emissions source in the U.S. is coal boilers in electricity generation units, the second biggest source of fossil fuel combustion is industrial boilers and ICEs. Among industrial processes, ferrous metals and cement manufacturing industries are the leading emissions industries. Waste disposal emissions is almost the same as cement manufacturing.

The results of state contribution analysis suggested various factors controlling mercury emission. High contributions to commercial/institutional, and waste disposal emission can be related to local population, while high contributions to residential emission can due to population as well as the needs for heating in low temperatures.

[13] Is It Better To Burn or Bury Waste for Clean Electricity Generation? P. Ozge Kaplan et al. Environ. Sci. Technol., 2009, 43 (6), pp 1711–1717

High contributions to specific industry implies the large scale of that industry, such as the contribution of Texas to petroleum refinery industry.

The 2014 mercury emissions from WTE industry in the U.S. were estimated to be 363 kg, which constituted 0.66% of all U.S. anthropogenic emissions. The average mercury emission per metric ton of MSW combusted in WTE plants was estimated at 0.013 grams. In the sanitary landfill sector, mercury emissions were estimated atfrom landfill is used, which is 654.82kg.

In this study, some discrepancies between data sources were found. Firstly, according to the 2014 NEI, 2014 mercury emissions from Municipal Waste Combustors is 0.8 tons, while according to this study this number is about 0.36 tons. The second discrepancy is the amount of MSW landfilled estimated by U.S. EPA, Columbia EEC, and Powell et al. (2015). In the year of 2011, EPA reported the MSW landfilled to be 134.2 million tons; but as reported by the fifty states to the Columbia survey it is 254.2 million tons. In 2012, EPA reported MSW landfilled to be 122 million tons, while according to Powell et al. (2015) it is 262 million tons using the "GHG reporting data" to estimate.

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