A Template for a State-of-the-Science Assessment of the Public Health Benefits associated with Mercury Emissions Reductions for Coal-fired Electricity Generating Units

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Executive Summary. We describe a technical approach using best-available scientific information to assess the public health benefits associated with reductions in mercury emissions from United States (U.S.) coal-fired electricity generating units (EGUs). We provide an example illustrating the calculations EPA could use to further bolster its findings supporting the Appropriate and Necessary (A&N) determination underlying the Mercury and Air Toxics (MATS) Rule.

For our example, we compare recent emissions in 2020 to 2008-2010 as a baseline period preceding MATS. We find there was a 90% reduction in mercury emissions from EGUs between 2008 (26.8 Mg) and 2020 (2.8 Mg) totaling 24 Mg. Our updated modeling from a state-of-the-science atmospheric model (GEOS-Chem) for the <u>same emission magnitude</u> as used in the 2022 A&N proposal suggests *average utility-attributable mercury deposition is approximately twice as large* as EPA's estimate. This increase in domestic deposition from coal-fired EGUs reflects improved understanding of the speciation of mercury released from coal-fired EGUs and atmospheric reactions of mercury that should be used in atmospheric modeling.

Results show average contemporary EGU-attributable deposition across the contiguous U.S. decreased by 91% between 2008 and 2020. At the sites most impacted by EGUs (99th percentile of EGU-attributable deposition) deposition decreased from 4.41 $\mu g\ m^{-2}\ yr^{-1}$ in 2008 to 0.39 $\mu g\ m^{-2}\ yr^{-1}$ in 2020.

We present a probabilistic modeling approach for quantifying mercury exposures for the U.S. general population and recreational fishers. Empirical data on seafood consumption by species and harvesting locations were used to parameterize this model. Meal frequency data were obtained from the National Health and Nutrition Examination Survey (NHANES, 2009-2018), and meal sizes were varied based on the distributions specified in EPA's Exposure Factors Handbook. A probabilistic version of EPA's one-compartment toxicokinetic model was used to convert external doses to blood and hair mercury concentrations. The modeling approach was constrained by the measured distribution of mercury in the U.S. population from NHANES (NHANES, 2009-2018). EGU-attributable exposures were calculated based on EGU-attributable deposition to relevant seafood harvesting regions for 10,000 probabilistically simulated individuals with 10,000 individual diets. We followed EPA's assumptions of proportional changes in fish mercury concentrations with shifts in atmospheric deposition and a 10-year time lag between deposition and fish mercury exposures.

Our modeling results suggest that reductions in EGU emissions between the 2008-2010 baseline and 2020 resulted in 60,000-100,000 women of childbearing age (16-49) shifting from above to below the EPA's Reference Dose (RfD) for methylmercury and 3700-5600 fewer babies born per year with exposures above the RfD. Using the same dose-response functions as used by EPA in their 2022 proposal, we estimate 2600 IQ points were lost prior to MATS due to EGU-attributable mercury and 700 IQ points were lost in 2020 (a difference of 1900 IQ points). Prior to MATS, 12% of these IQ losses were associated with recreational fish consumption, and 27% associated with legacy mercury from historical U.S. EGU emissions. In 2020, 7% of total EGU IQ losses were associated with recreationally caught fish consumption and 71% were associated with legacy mercury from historical U.S. EGU emissions. These estimates can be viewed as a lower bound for IQ deficits associated with mercury emissions from EGUs because the dose-response relationship between methylmercury and IQ loss is

steeper once corrections for the confounding effects of omega-3 fatty acids in fish are considered.

Our modeling results suggest that reductions in EGU mercury emissions between the 2008-2010 baseline and 2020 decreased the share of the U.S. population exposed at levels above those associated with increased risk of ischemic heart disease by 380,000 individuals, and the share exposed at levels above those associated with increased risk of cardiovascular mortality by 160,000 individuals (Hu et al., 2021). We estimated 146 premature CVD mortalities were avoided due to declines in EGU-attributable mercury between the 2008-2010 baseline (204 premature mortalities) and 2020 (58 premature mortalities). We estimate that 71% of benefits are attributable to individuals in the general population and 29% to recreational fishers. Reductions in EGU-attributable legacy mercury accounted for 10% of the benefits, and 90% were from contemporary emissions reductions.

To monetize benefits, we used two discount rates (1% and 3%) that are more consistent with updated data on the social rate of time preference than values used by EPA (3% and 7%). We estimated the public health costs due to EGU attributable IQ deficits declined by $25 million USD between 2010 and 2020 at a 3% discount rate, and $55 million USD at a 1% discount rates. This estimate is based on individual lifetime earnings changes as a function of IQ. It is likely an underestimate of the costs to society because it does not account for contributions to wellbeing other than increased labor-force productivity; for example, it does not reflect the societal costs of large-scale shifts in population IQ distributions that could reduce the number of innovators in society, decrease population health and increase the number of individuals that rely on the state for care.

Public health benefits of reduced premature cardiovascular mortalities due to decreases in EGU-attributable mercury emissions between 2010 and 2020 accounted for $1.2 billion USD at a 3% discount rate and $1.5 billion USD at a 1% discount rate. These values exceed the upper bound for EPA's analysis of $1.1 billion USD based on EGU-attributable emissions in 2016 with a 3% discount rate. We estimate the total cost of premature cardiovascular mortality due to EGU-attributable mercury emissions in 2020 to be $500 million (90%: $1.5 billion), compared to $1.7 billion USD (90%: $3.3 billion) in 2010.

The monetized health benefits in our assessment represent lower bounds for the public health benefits associated with reductions in EGU-attributable mercury emissions because they do not include: (1) neurodevelopmental effects associated with mercury exposure on lifetime earnings such as memory, delayed learning, and behavioral impacts; (2) impacts on wildlife; and (3) they represent a lower bound for impacts on recreational fishers because seafood consumption magnitudes were constrained within the distribution reported by NHANES, which under-samples high-frequency fish consumers (95th percentile) who are most vulnerable to mercury exposures.

NHANES data show disproportionate mercury exposures occur for certain ethnicities (Asian, Pacific and Caribbean Islander, Native American, Alaska Native, multi-racial) and socioeconomic groups (low income, education levels). Further consideration of the environmental justice implications of the remaining coal fired EGUs across the U.S. is thus warranted.

Background: The United States (U.S.) Environmental Protection Agency (EPA) released their revised analysis supporting the Appropriate and Necessary (A&N) determination underlying the Mercury and Air Toxics Standards (MATS) on January 31, 2022. There are several shortcomings in the revised analysis that we have highlighted in previous work, most recently the white paper released on the Harvard C-CHANGE website in December 2021: https://www.hsph.harvard.edu/c-change/news/mercury-science-and-the-benefits-of-mercury-regulation/

Here, we provide a technical approach with example calculations of a methodology EPA could use to further bolster their findings by using best-available scientific information to support the rule. This report includes the following sections on our methods for analyzing the exposure pathway for mercury and health benefits associated with the MATS rule**: 1) Emissions, 2) Deposition, 3) Exposure, 4) Health Outcomes, 5) Monetized Benefits, and 6) Environmental Justice.**

1. **Emissions**

In EPA's 2022 proposal, mercury emissions from electricity generating units (EGUs) were projected from modeling conducted as part of past regulatory activities (around 2005) for the year 2016 as a baseline (26.3 Mg or 29 Imperial tons). No post-MATS EGU emissions were considered in EPA's analysis.

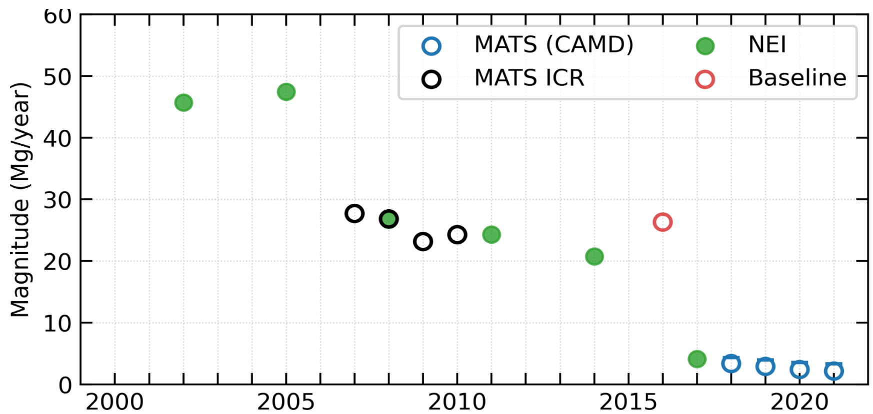

Figure 1| Temporal changes in mercury emissions from U.S. coal-fired electricity generating units. Green circles show reported emissions from the US EPA *National Emissions Inventory* (NEI), black circles show the Mercury and Air Toxics Standards Information Collection Request (MATS ICR), the red circle shows the projected baseline value used in the 2022 proposal by EPA, and blue circles show recent MATS hourly reporting data. Blue dashes on the upper part of blue circles represent upper-bound emissions from low-emitting coal EGUs exempted from hourly reporting requirements.

Our example is based on 2008-2010 as a baseline period relative to 2020. The Mercury and Air Toxics Standards (MATS) rule was promulgated in 2011. Thus, mercury emissions from U.S. coal-fired electricity generating units from the MATS Information Collection Request (MATS ICR) prior to this rule (ca. 2008, 26.8 Mg) are used as a baseline for assessing the direct benefits of the regulation (*Figure 1*). Plant-specific reporting data for 2020 are used to assess the post-MATS mercury emissions level (2.8 Mg). Emissions values between 2019-2021 have stabilized in recent year at a low level.

We find there was a 90% reduction in mercury emissions from EGUs between 2008 (26.8 Mg) and 2020 (2.8 Mg) totaling 24 Mg.

2. **Deposition**

EPA relied on outdated atmospheric modeling in their assessment of EGU-attributable mercury exposures for subsistence fishers and conducted a screening analysis for the general population based only on projected emissions for 2016. To create an upper bound scenario for general population exposures, EPA's modeling suggested that the fraction of total deposition (18.7 μg m^{-2} yr^{-1}) attributable to EGUs (f_{EGU}) was 1.8% based on modeled average EGU-attributable deposition to U.S. ecosystems of 0.34 μg m^{-2} yr^{-1}.

***Deposition from contemporary emissions**:* Our updated modeling from a state-of-the-science atmospheric model (GEOS-Chem) for the same emission magnitude suggests *average utility-attributable mercury deposition is approximately twice as large* as the EPA's estimate. This increase in domestic deposition from coal-fired EGUs reflects improved understanding of the speciation of mercury released from coal-fired EGUs and atmospheric chemistry. Results of deposition scenarios for 2008 and 2020 are shown in *Figure 2*.

Deposition from legacy mercury: EPA did not consider the long lifetime of utility-derived mercury in the environment. After mercury from coal-fired EGUs is deposited to ecosystems, some is reemitted and continues to cycle in the global environment where it can accumulate in the commercial seafood that people eat. In our analysis, we estimate the global legacy of cumulative U.S. utility-derived mercury emissions from Streets et al. (2019) using a global biogeochemical box model (Amos et al., 2013, 2014). We used the model to quantify the contribution to global deposition from cumulative U.S. EGU emissions in 2010 (1.0%) and 2020 (0.89%) that is still actively cycling in the biosphere and thus contributes to background deposition from all sources. This contribution to background deposition is an important contributor to mercury exposures from global ocean seafood harvests (*Figure 3*).

For our analysis, we consider changes in deposition to ecosystems supplying fish consumed by the U.S. population between the 2008- 2010 baseline and 2020. Results show average contemporary EGU-attributable deposition across the contiguous U.S. decreased by 91% between 2008 and 2020. At the most EGU-impacted sites (99^{th} percentile of EGU-attributable deposition) deposition decreased from 4.41 μg m^{-2} yr^{-1} in 2008 to 0.39 μg m^{-2} yr^{-1} in 2020. We estimate that the contribution of legacy U.S. EGU emissions to global deposition declined from 1.0% in 2010 to 0.89% in 2020.

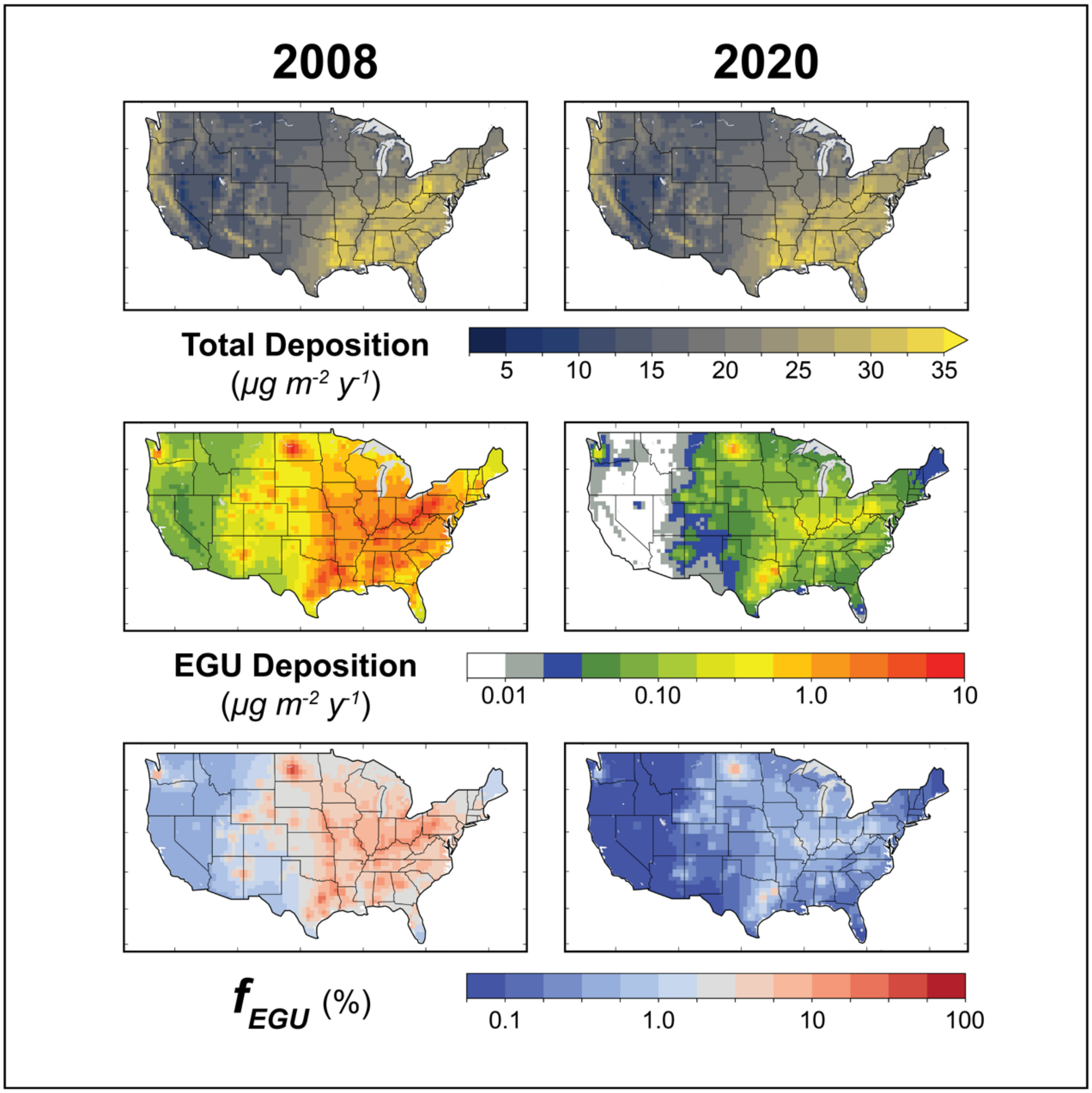

Figure 2| Modeled atmospheric mercury deposition before (2008) and after (2020) implementation of the Mercury and Air Toxics Standards (MATS). Results are based on a nested simulation (0.5°x0.625° horizontal resolution) using the GEOS-Chem global chemical transport model described in Shah et al. (2021). Total deposition (top panels) shows mercury deposited from all sources. The middle panels show deposition originating from only U.S. coal-fired electricity generating units (EGU deposition). The fraction of total mercury deposition from EGUs (f_{EGU}) is shown on the bottom panels.

3. Mercury Exposures

General population mercury exposures: We appreciate that EPA included a bounding-analysis of general population exposures to mercury through the commercial seafood market based on emissions in the 2022 proposal. This inclusion is essential because the commercial seafood market is the main exposure pathway for Americans. However, we suggest that EPA more fully quantify the exposure pathway for general population exposures instead of simply relying on EGU emissions as a fraction of the global total for the lower bound, and average utility-derived deposition across the contiguous U.S. for the upper bound. These types of bounding analyses do not consider the large variability in utility-attributable deposition in fish harvesting regions that are important for U.S.

consumers and ignore best-understanding of human exposure patterns. Further, the average utility-attributable deposition was underestimated (as described in section 2).

We present a probabilistic modeling approach based on established tools and data for simulating changes in mercury exposures between the 2008-2010 baseline and 2020 (*Figures 3-6*). We simulated 200 iterations of this model for 10,000 representative U.S. individuals in the general population. Inputs to the model include 10,000 randomly generated seafood diets (one per individual) based on probabilities assigned to differing types and harvesting origins of seafood in the commercial market that reflect consumption patterns by the general population (Sunderland et al., 2018).

The number of seafood meals is based on data from the National Health and Nutrition Examination Survey (NHANES 2009-2018) and meal sizes are based on the distribution reported in EPA's 2011 Exposure Factors Handbook (US EPA, 2011). Baseline general population exposures are based on these seafood ingestion rates combined with distributions of species-specific mercury concentrations from the literature (Karimi et al., 2012, Sunderland 2007, Sunderland et al., 2018). The ingested dose of mercury for each of the 10,000 simulated individuals is converted to a blood or hair mercury concentration using a previously published probabilistic version of EPA's one-compartment toxicokinetic model (Li et al., 2016). We ensure that the baseline (ca. 2010) simulated distribution of blood mercury concentrations is consistent with that measured in NHANES (2009-2018).

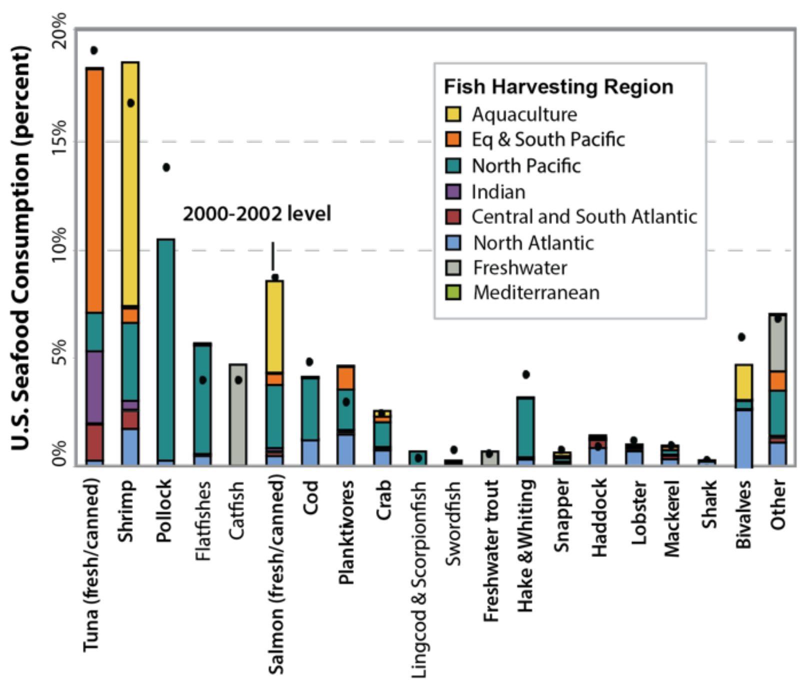

Figure 3| Seafood consumption by the U.S. general population and their harvesting origins based on the edible supply of fish sold domestically in the commercial market. Figure adapted from Sunderland et al. (2018). Bars show data for the years 2010-2012 and dots show the total for years 2000-2002.

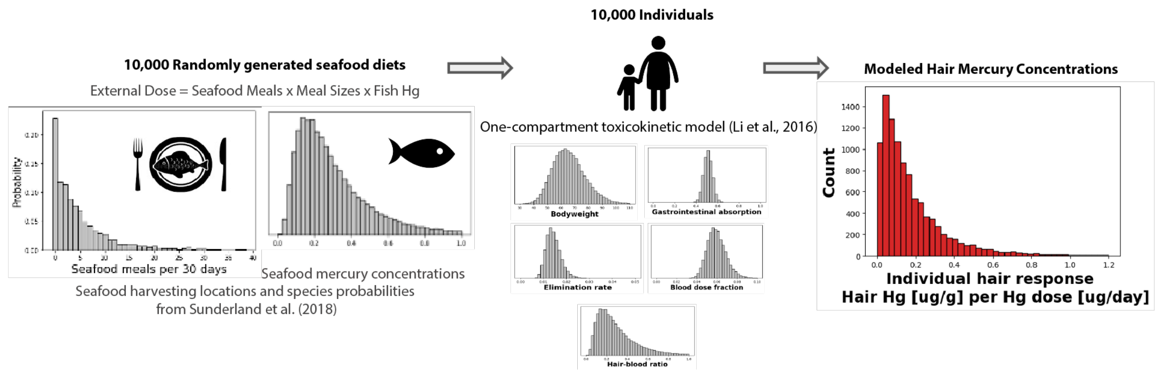

Figure 4. Schematic of probabilistic model used to simulate general population exposures to EGU-attributable mercury. Number of seafood meals is based on NHANES (2009-2018) data for U.S. population. Meal size distribution is from EPA's Exposure Factors Handbook (US EPA, 2011). Distributions of fish mercury concentrations are from Karimi et al. (2012). Species preferences and harvesting locations are from Sunderland et al. (2018). Distributions of parameters used in one-compartment toxicokinetic model is from Li et al. (2016).

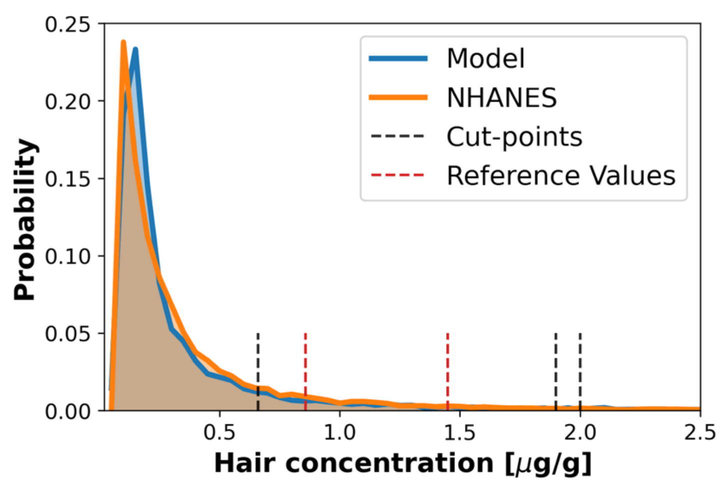

Figure 5| Comparison of modeled hair mercury concentrations (blue) for 10,000 randomly simulated individuals with the distribution of hair mercury corresponding to blood mercury data from NHANES (orange) (2009-2018). Red dashed vertical lines show the hair equivalent to the EPA Reference Dose (RfD equivalent for blood = 5.8 μg L^{-1}) for methylmercury and the lower corresponding value for maternal blood concentrations (3.5 μg L^{-1}) converted to hair equivalents that expose the fetus at the RfD. Black dashed lines show cut-points for cardiovascular mortality risks used by EPA in their 2022 proposal based on the epidemiological literature.

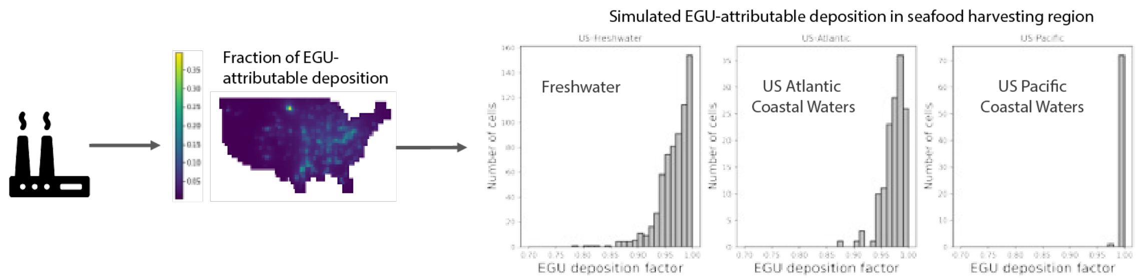

Figure 6| Schematic of method used to simulate EGU-attributable mercury for each fish harvesting region for the U.S. general population. The fraction of mercury deposited from EGUs to different major fish harvesting is simulated using the GEOS-Chem atmospheric chemistry transport model (Figure 2). We aggregated major fisheries harvesting regions relevant to U.S. individuals who consume seafood from the commercial market (Figure 3) into the following: (1) U.S. domestic waterbodies, (2) US Atlantic coastal waterbodies, (3) US Pacific coastal waterbodies, and (4) global background deposition representing aquaculture species and open ocean fish (not shown). The EGU attributable mercury deposition to each region is represented as a probability density function that captures spatial variability in EGU inputs. For the contiguous U.S., deposition is only included for model grid cells with more than 1% lake surface area We follow EPA's assumption of a proportional change in fish mercury with shifts in atmospheric inputs and a 10-year lag time. Differences over time are calculate based on shifts in EGU-attributable emissions.

The EGU contribution to exposures is determined by following EPA's assumption that seafood mercury concentrations change in proportion to the shift in deposition to the harvesting region for each type of fish (*Figure 6*). Changes between the 2008-2010 baseline and 2020 were similarly assessed based on shifts in deposition between these periods. Changes in fish mercury burdens are realized 10-years after the deposition reduction, and public health benefits are calculated based on this discounting period.

Distributions of EGU-attributable deposition that reflect modeled spatial variability are applied to three main types of seafood harvesting locations. These include: 1) freshwater bodies across the contiguous U.S., 2) Atlantic coastal U.S. waters, 3) Pacific coastal U.S. waters. The U.S. EGU contribution to globally sourced seafood and aquaculture is estimated from utility emissions as a fraction of global emissions. Deposition to U.S. freshwater bodies is based on GEOS-Chem (nested-grid 0.5x.625) cells with more than 1% lake surface area.

Method for assessing recreational fisher mercury exposures*:* EPA did not enumerate benefits associated with decreases in EGU-attributable mercury exposures for recreational fishers. However, the U.S. Fish and Wildlife Service estimates that more than 10% of the U.S. population consumes recreationally caught fish from domestic waters.

For this analysis, we simulated exposures from recreationally caught fish similarly to the simulation for the U.S. general population but included a fraction of total fish consumption from recreationally caught species from national survey data (von Stackelberg et al., 2017). We used data on mercury concentrations reported for commonly consumed recreationally caught species and harvest locations from recreational fishing surveys. The distributions of EGU-attributable deposition affecting recreationally caught fish species were modeled independently for five U.S. regions with: 1) Northeast (2.0-4.9 million fishers), 2) Mid-Atlantic (0.2-0.4 million fishers), 3) Southeast (5.9-15 million fishers), 4) Midwest (8.1-20 million fishers), 5) West (6.6-17 million fishers) (Fish and Wildlife Service, 2002). Average U.S. concentrations for recreationally caught species were weighted regionally by variability reported in the United States Geological Survey (USGS) national fish tissue mercury database developed by Wente (2004).

4. Health Impacts of Exposure

Neurocognitive Health Impacts: EPA estimated that 1600-6000 IQ points would be lost in the U.S. general population due to the projected mercury emissions levels from EGUs in 2016 used for their analysis.

Our modeling results suggest that reductions in EGU emissions between the 2008-2010 baseline and 2020 resulted in 60,000-100,000 women of childbearing age (16-49) shifting from above to below EPA's Reference Dose (RfD) for methylmercury and 3700-5600 fewer babies born per year with exposures above the RfD.

Using the same dose-response functions as used by EPA in their 2022 proposal, we estimate 2600 IQ points were lost immediately prior to MATS due to EGU-attributable mercury and 700 IQ points were lost in 2020 (difference of 1900 IQ points). Prior to MATS, 12% of these IQ losses were associated with recreational fish consumption, and 27% were associated with legacy mercury from historical U.S. EGU emissions. In 2020, 7% of total EGU IQ losses were associated with recreationally caught fish consumption and 71% were associated with legacy mercury from historical U.S. EGU emissions. These estimates can be viewed as a lower bound for IQ deficits associated with EGU mercury emissions because the dose-response relationship for methylmercury and IQ is steeper once corrections for the confounding effects of omega-3 fatty acids in fish are considered (Choi et al., 2008).

Cardiovascular Health Impacts: EPA's analysis in the 2022 proposal made important advances by considering cardiovascular mortality due to mercury exposures (*Figure 7*). However, it included only considered mortalities attributable to acute myocardial infarction, which represents only a small fraction (~100,000) of total cardiovascular mortalities in the U.S (>700,000) (CDC, 2021). Results of the EPA bounding analysis for 2016 projected emissions suggested 5-91 premature mortalities occurred in the U.S. population due to EGU-attributable mercury exposures.

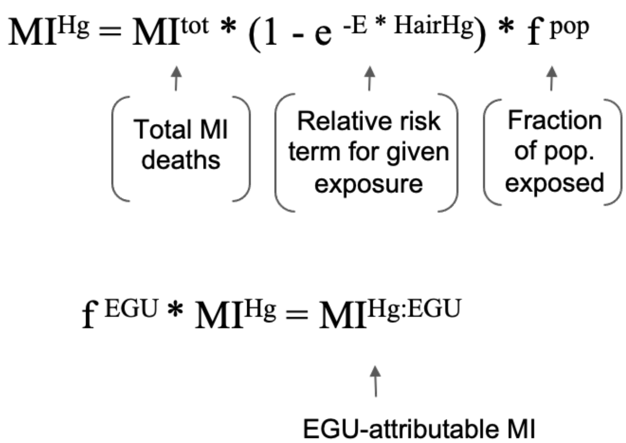

Figure 7| Overview of EPA method for estimating acute myocardial infarction mortalities (MI) in the U.S. general population attributable to coal-fired EGUs. Total MI attributed to mercury exposures (MI^{Hg}) is calculated as a fraction of total MI deaths in the U.S. population for 2016 (110,000). MI^{Hg} is based on the relative risk expressions in the epidemiological literature (reviewed in Hu et al., 2021) for MI based on hair mercury concentrations (*HairHg*). The effect estimate (-*E* = mean: 0.10, 95th CI = 0.06-0.16) for relating HairHg to MI mortality is based on Roman et al. (2011) and Virtanen et al. (2004). The fraction of the U.S. population (f^{pop}) above the cutpoints for human mercury exposure that correspond to MI risks is based on NHANES. EGU attributable MI ($MI^{Hg:EGU}$) is calculated using bounding scenarios for utility-attributable mercury (f^{EGU}). The lower bounding scenarios for f^{EGU} is based on projected 2016 emissions as a fraction of total global emissions (0.48%). The upper bounding scenario is based on projected 2016 EGU-attributable deposition as a fraction of total domestic deposition (1.8%). Uncertainties in these bounds are described based on our analysis in sections 1-2 of this whitepaper.

Two systematic reviews of the association between methylmercury exposure and heart disease showed that methylmercury enhances production of free radicals resulting in a long-lasting range of effects on cardiac parasympathetic activity, such as myocardial infarction, hypertension, blood pressure, and death (Genchi et al., 2017; Hu et al., 2021). Thus, we consider total cardiovascular mortality (CVD) in addition to acute MI mortality based on relative risk expressions from Hu et al. (2021). This expression uses essentially the same functional form as shown in *Figure 7*, but the total mortality and relative risk (RR) estimates differ. (i.e., $CVD^{Hg} = CVD^{tot} \times (1-1/RR) \times f(HairHg > 2.0 ug/g)$). CVD^{tot} is the number of total CVD deaths annually for each year considered in the U.S. (790,000 in 2010 and 700,000 in 2020); *RR* is the relative risk (1.68, Hu et al., 2021) of CVD death for hair Hg concentrations > 2.0 µg/g; and $f(HairHg_r > 2.0\ \mu g/g)$ is the fraction of the population with hair concentration above 2.0 µg/g.

Our modeling results suggest that reductions in EGU mercury emissions between the 2008-2010 baseline and 2020 reduced the U.S. population exposed at levels above those associated with increased risk of ischemic heart disease (Hu et al., 2021) by 380,000 individuals. Mercury exposures for an estimated 160,000 individuals were reduced below those associated with increased risk of cardiovascular mortality (Hu et al., 2021) due to reductions in mercury emissions from EGUs following MATS implementation.

The modeled reduction in premature CVD mortalities due to declines in EGU-attributable mercury was 146 individuals between the 2008-2010 baseline and 2020.

Table 1| Modeled premature mortalities attributable to EGU mercury emissions (with 90th percentile CVD mortality in parentheses).

EGU-attributable mortalities	2008-2010 baseline	2020 (post-MATS)	Difference 2010-2020
Recreational fishers	61 (114)	18 (43)	43 (70)
% total premature mortality	*30%*	*31%*	*29%*
U.S. general population	143 (266)	40 (96)	103 (170)
% total premature mortality	*70%*	*69%*	*71%*
Total CVD mortality	**204 (380)**	**58 (140)**	**146 (240)**
Legacy EGU mercury (% total)*	*29%*	*76%*	*10%*
MI mortality (% total)	*21% (14%)*	*19% (12%)*	*21% (15%)*

*Legacy mercury exposures are included for both recreational fishers and the U.S. general population.

5. Monetized benefits of MATS

EPA monetized public health costs of EGU-attributable mercury based on lifetime earnings discounted to net present values as a function of IQ and the value of a statistical life (VSL) for premature mortalities in 2016 dollars. EPA used discount rates of 3% and 7% resulting in $8,000-$11,900 in costs per IQ point lost and a VSL of $10.7 million 2016 dollars for each premature mortality. The 3% and 7% discount rates are consistent with the Office of Management and Budget (OMB) Circular A-4 (OMB, 2003), although Circular A-4 states that for rules with important intergenerational effects, agencies should also conduct a sensitivity analysis with a discount rate between 0% and 3%.

Since this OMB circular was issued, there have been significant developments in both interest rates and understanding of how projects should be discounted (CEA 2017). The 3% rate is motivated as the social rate of time preference and is an estimate of "the real rate of return on long-term government debt" (OMB 2003, p. 33). The Council of Economic Advisers shows that real interest rates have decreased in the US and other Organization for Economic Cooperation and Development (OECD) countries since Circular A-4 was issued and that plausible estimates of the social rate of time preference are "at most 2 percent" (CEA 2017, p. 12). The 7% rate is motivated as the opportunity cost of capital and is "an estimate of the average before-tax rate of return to private capital in the U.S. economy" (A-4 p. 33). CEA (2017) suggests this rate should also be decreased, in part because interest rates have declined and possibly because it excludes unpriced externalities and includes returns to market power and compensation for risk. In addition, arguments based on the Ramsey rule and on uncertainty about future economic growth suggest that discount rates for long horizons should be smaller (as recognized by Circular A-4 and implemented in British and French guidance documents; see, e.g., Gollier and Hammitt 2014).

We therefore used discount rates of 3% and 1% in our analysis. In 2020 dollars, VSL was considered to be $11.5 million and mortality was discounted for a lag time of 10 years following the reduction in EGU-attributable deposition. Based on a 3% discount rate for lifetime earnings, we estimated a cost of $8,500-$12,500 per IQ point decrement ($19,500 - $28,000 with 1% discount rate).

The public health costs due to EGU-attributable IQ deficits are estimated to have declined by \$25 million USD between 2010 and 2020 at a 3% discount rate, and \$55 million USD at a 1% discount rates. This estimate is based on changes in IQ for births in each year driving changes in individual lifetime earnings, accounting for median wages, survival probability, and labor force participation at each age, discounted back to the year of birth. It is likely an underestimate of the costs to society because it does not account for contributions to wellbeing other than increased labor-force productivity; for example, it does not reflect the societal costs of shifts in population IQ that could reduce the number of innovators in society, decrease population health and increase the number of individuals that rely on the state for care.

Changes in EGU-attributable premature cardiovascular mortalities between 2010 and 2020 are valued at \$1.2 billion USD at a 3% discount rate and \$1.5 billion USD at a 1% discount rate. These values exceed the upper bound for EPA's analysis of \$1.1 billion USD based on EGU-attributable emissions in 2016. The total cost of premature cardiovascular mortality due to EGU-attributable mercury emissions is estimated to be \$500 million (90^{th}%: \$1.5 billion) in 2020 and \$1.7 billion USD (90^{th}%: \$3.3 billion) in 2010.

The monetized health benefits in this assessment are still lower bounds for the public health benefits associated with reductions in EGU-attributable mercury emissions because: (1) the analysis did not include any of the neurodevelopmental effects associated with mercury exposure other than IQ impacts on lifetime earnings such as memory, delayed learning, and behavioral impacts; (2) they do not include an assessment of the impacts on wildlife; and (3) they represent a lower bound for impacts on recreational fishers because seafood consumption magnitudes were constrained within the distribution reported by NHANES, which undersamples high-frequency fish consumers (95^{th} percentile) who are most vulnerable to mercury exposures.

6. **Environmental Justice**: Disproportionate mercury exposures occur for individuals with lower socioeconomic status, education, and certain minority ethnicities (Sunderland et al., 2021). A preliminary spatial analysis (*Figure 8*) of the locations of low income and minority populations reveals the need for more detailed consideration of how these already vulnerable communities are affected by remaining EGUs.

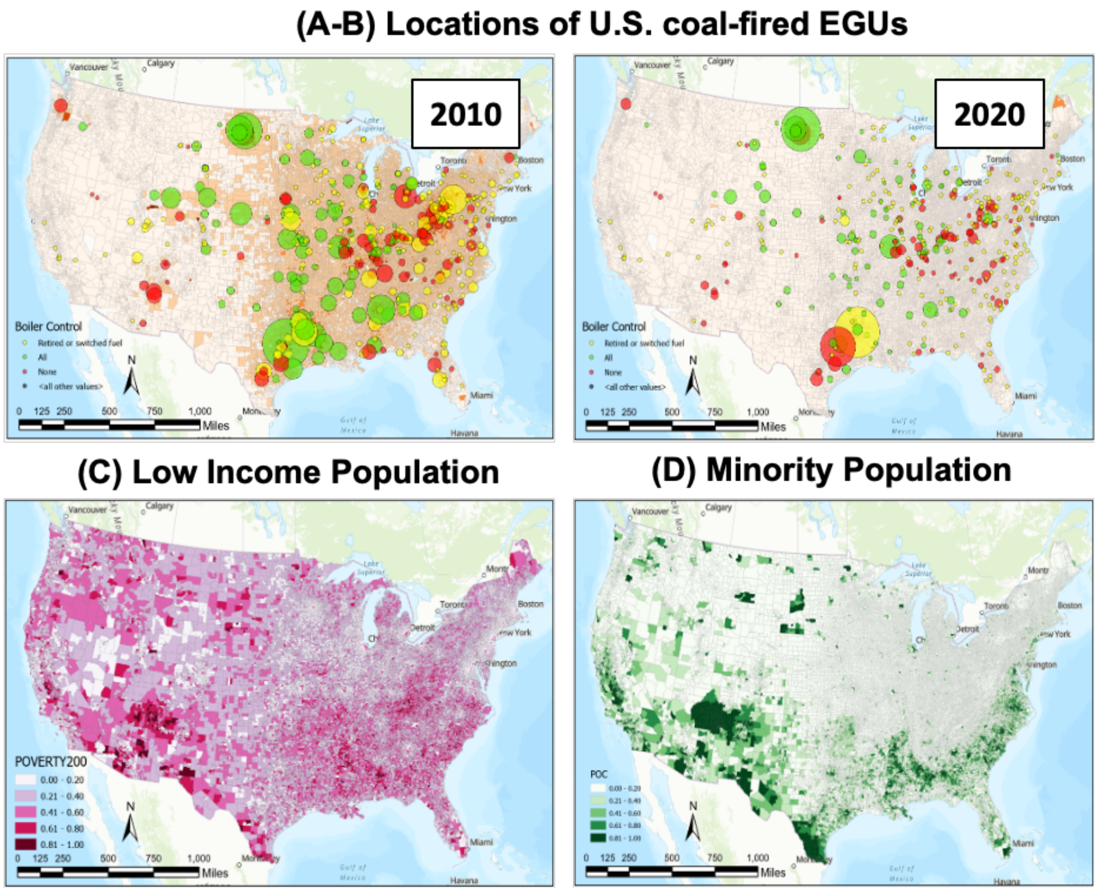

Figure 8| Locations of U.S. coal fired EGUs in 2010 and 2020 and corresponding locations of low-income and minority communities. Panels A-B show locations of EGUs, indicated by circles with varying sizes that reflect mercury emissions magnitudes. Color of circles indicates the control technologies on boilers. Yellow circles indicate EGUs that have retired or switched fuel source away from coal. Green circles indicate all boilers have emissions control technologies in place. Red circles indicate no boilers have emissions controls. Average EGU-attributable mercury deposition for census block groups is shown by shading next to EGUs, with higher emissions denoted by darker colors. Panel (C) shows proportion of census block groups within 200% of poverty line, with higher proportions of poverty indicated by darker colors. Panel (D) shows the locations of census blocks with high proportions of minorities indicated by darker green colors.

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