

Impact of Glasgow Climate Pact and Updated Nationally Determined Contribution on Mercury Mitigation Abiding by the Minamata Convention in India

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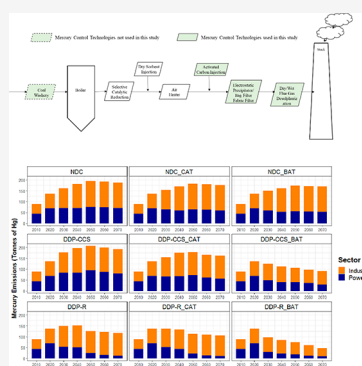
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ABSTRACT: India is one of the largest emitters of atmospheric anthropogenic mercury (Hg) and the third-largest emitter of greenhouse gases in the world. In the past decade, India has been committed to the Minamata Convention (2017) in addition to the Paris Climate Change Agreement (2015) and the Glasgow Pact (2021). More than 70% to 80% of India's mercury and carbon dioxide emissions occur because of anthropogenic activities from coal usage. This study explores nine policy scenarios, the nationally determined contribution (NDC) scenario, and two deep decarbonization pathways (DDP) with and without mercury control technologies in the energy and carbon-intensive sectors using a bottom-up, techno-economic model, AIM/Enduse India. It is estimated that NDC scenarios reduce mercury emissions by 4%–10% by 2070; while coal intensive (DDP-CCS) pathways and focus on renewables (DDP-R) reduce emissions by 10%–54% and 15%–59%, respectively. Increase in the renewables share (power sector) can result in a significant reduction in the costs of additional pollution-abating technologies in the DDP-R scenario when compared with the coal intensive DDP-CCS scenario. However, the industry sector, especially iron and steel and metal production, will require stringent policies to encourage installation of pollution-abating technologies to mitigate mercury emissions under all the scenarios.

KEYWORDS: Glasgow Pact, decarbonization, Minamata Convention, mercury, integrated assessment modeling, India



1. INTRODUCTION

Mercury is considered an extremely harmful pollutant, as it is a potent neurotoxin (in the form of methylmercury) to humans as well as animals. Mercury pollution through emissions, water, and soil influences a chain of physical as well as bio-geochemical processes. Multilateral Environmental Agreements (MEA) such as Basel (1989), Rotterdam (1998), and Stockholm (2001) have focused on hazardous chemicals, pesticides, and wastes, in addition to persistent organic pollutants (POPs) that have included mercury.^{1–3} India is not a primary producer of mercury; however, it is released as byproduct of coal (bituminous, sub-bituminous, lignite) combustion, petroleum production, iron and steel production, cement production, non-ferrous metal production (copper, lead, zinc), and other uses of coal (industry). The Minamata Convention on Mercury agreed in 2013 and entered into force in 2017 focuses on anthropogenic emissions of mercury and its compounds.⁴ India is the second largest emitter of atmospheric mercury (Hg) in the world.^{5,6} Coal is considered one of the largest sources of anthropogenic mercury emissions at global and national levels.⁷ India became a signatory to the Minamata Convention (MC) on 30th September 2014 and ratified the agreement on 18th June 2018.⁸ Prior to the MC, India had several policy instruments implemented under the Air (Prevention and Control of Pollution) Act 1981, and the

Environment (Protection) Act 1986 pertaining to emissions. India is a party to all the conventions leading to the formulation and amendments of environmental regulations; however, the implementation has not been effective.^{9,10}

India constitutes the second largest population (17% of the world population in 2022), one of the fastest-growing economies, globally the second largest producer and consumer of coal, and the third largest consumer of energy in addition to being the third largest emitter of carbon dioxide (CO₂). As one of the largest developing countries, India has planned and implemented initiatives, as well as incremental development policies in every sector. The energy sector in India contributes to more than 75% of the GHG emissions of which the power and industry sectors contribute to 40% and 19%, respectively, in 2016.¹¹ In addition to GHG emissions, the growing energy demand due to urbanization and industrialization also affect the local air quality.¹¹ The Copenhagen Accord (2009), the

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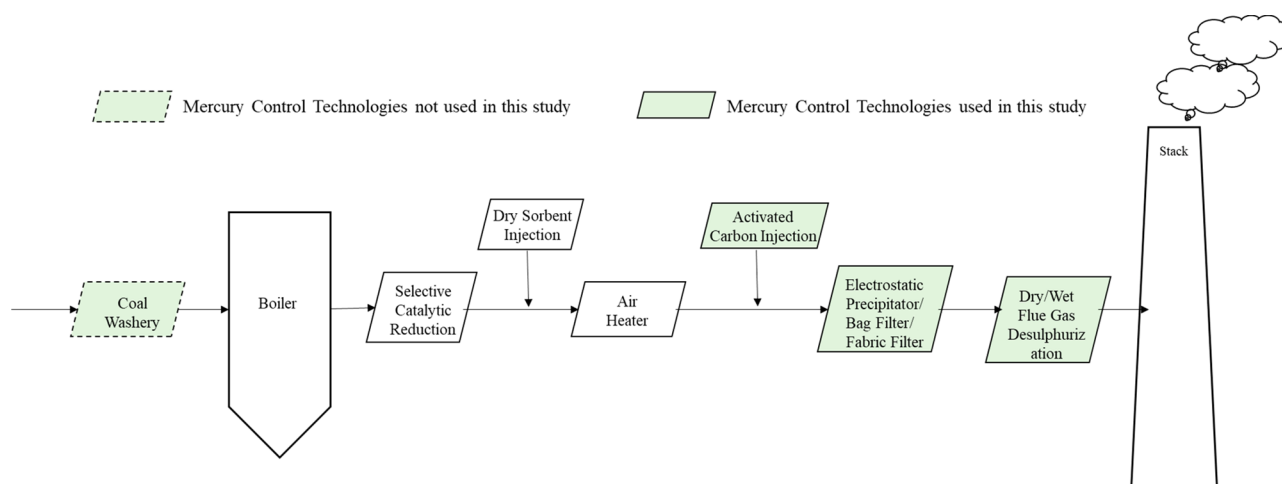


Figure 1. Mercury Control Technologies (end-of-pipe) taken into consideration for the current study.

Paris Agreement (2015), and the Glasgow Pact (2021) have committed countries around the world to reduce their emissions to 1.5 °C.^{12–14} The Glasgow Climate Pact aims to turn the 2020s as the decade for climate action through curbing greenhouse gas emissions, building resilience to climate change, and providing finance necessary for implementation. Nations for the first time have been called upon to phase down unabated coal and inefficient subsidies for fossil fuels.¹⁴ This paper focuses on curbing greenhouse gas emissions and the coal phase aspect of the Glasgow Pact. Additionally, India is also committed to the Sustainable Development Goals (SDGs) relating to energy access and security, air quality, poverty alleviation, employment creation, sustainable production, and consumption.¹⁵

Multiple national studies have focused on India's decarbonization pathways over the past decade, capturing the planned and implementation of climate and development policies. These studies have considered individual technologies (nuclear, solar, and so on), individual systems (power, transport, buildings), and structural systemic changes as well as overall energy systems.^{16–21} Furthermore, it has been stated that low-carbon pathways have multiple co-benefits both on human health and environment. Studies have explored the effect of the implementation of air pollution policy instruments on air quality. These studies have looked at one or multiple pollutants such as primary sulfur dioxide (SO₂), oxides of nitrogen (NO_x), ammonia (NH₃), particulate matter (PM₁₀ and PM_{2.5}), ozone (O₃), and non-methane volatile organic compounds (NMVOC) and their impacts on human health.^{22–26} Global studies have considered the impact of decarbonization pathways on air quality as well as their influence on the quality of health.^{27,28} In the case of mercury emissions, studies have focused on the historical analyses of mercury emissions at the global⁷ and country level especially for India.^{5,6,9,29} Studies have analyzed the mercury projections especially from the power sector and have analyzed the costs and benefits of mercury emission reductions.^{30–32} However, limited studies have investigated the impact of decarbonization projections on mercury emissions at global and regional levels.^{30,33,34} There are no studies that have explored the impact of the Paris Agreement and the Glasgow Pact on the Minamata Convention (mercury emissions), especially at national and sectoral levels for India.

In this article, the methodology (section 2) describes the Indian energy systems using a bottom-up, techno-economic model. The novel contribution of this study is an investigation of the impact of decarbonization pathways on mercury emissions in India. It also explores the impact of end-of-pipe technologies on mercury emission (section 3). We have examined the co-benefits and trade-offs across nine policy scenarios, namely, the national determined contribution (NDC) scenario and two deep decarbonization pathways (DDP) in the energy and carbon-intensive sectors (power and industry) (section 4). Section 5 concludes by summarizing the results, insights, and limitations of the study.

2. METHODOLOGY

2.1. Model Development. The AIM/Enduse-India model has been used in this study to capture existing and future energy and sectoral policies related to emissions reduction, resource efficiency, and controlling environmental pollution. The model focuses on both the energy supply (power generation) and energy end-use sectors (industry, transport, buildings, and agriculture). Further information about the model description (Figure S1) is provided in the Supporting Information section. We have extended the model until 2070 as India during the Glasgow Pact has committed to being Net Zero by 2070.

The study focuses on the impact of mercury emissions due to decarbonization and end-of-pipe technologies. In this study, we extended the AIM/Enduse India national model by adding end-of-pipe technologies to capture mercury mitigation. Mercury mitigation can be done pre-combustion and post-combustion of fossil fuel transformation in addition to industrial processes such as the use of raw materials (ore concentrates and limestone). Pre-combustion includes treatment of coal through coal washing, blending, additives, and beneficiation which reduces ash, sulfur, and mercury content of the coal. In this study, we have not considered precombustion technology. Post-combustion technologies for mercury mitigation include activated carbon injection (ACI), electrostatic precipitator (ESP), bag filter (BF), fabric filter (FF), and dry/wet flue gas desulphurization (FGD). ACI technology is a mature commercial technology, where activated carbon is used as an effective sorbent for mercury from flue gas. ESP is a technology that uses a high intensity electric field to capture the dust particles (mercury). Fabric filter/bag filters/baghouses

are technologies that use a filter media to capture dust particles (mercury). Flue-gas desulphurization is a technology that primarily removes sulfur dioxide from exhaust flue gases; however, in the process also removes mercury as well. In this study, we considered mercury emissions from both fuel combustion and industrial processes. We have captured single technologies such as ESP, ACL, FGD, and FF as well as advanced types of mercury mitigation technology such as ESP-FF in deep decarbonization scenarios. Most of these technologies to mitigate mercury are used in both the power and the industry sectors.^{35,36,37} Figure 1 presents the end-of-pipe technologies for mercury mitigation included in the model. Further information about the mercury content in ores and product by sector (Table S3) and technologies used to mitigate mercury (Table S4) is explained in the Supporting Information. The cost of these have been summarized based on secondary peer-reviewed and gray literature.^{7,38,39} It is to be noted that we cannot separately estimate the cost of mitigating mercury, as the technologies selected by the model are also used for air pollution control. The power and industry sectors will install these technologies to control/reduce both air pollution and mercury emissions.

2.2. Scenario Description. Three different decarbonization pathways are analyzed to discuss current and alternative future scenarios in energy-intensive sectors, i.e., the power sector from an energy supply perspective and the industry sector from an enduse energy demand perspective.

2.2.1. National Determined Contribution (NDC) Scenario. The baseline scenario encompasses currently implemented policies included in the Indian National Action Plan on Climate Change (NAPCC), and National Determined Contribution (NDC) as submitted under the Paris Agreement in 2015. The scenario goals include a reduction in GHG intensity of Indian GDP by 33–35% during 2005–2030 (NDC Goal 3) and an increase in non-fossil energy share to 40% of total electricity capacity by 2030 (NDC Goal 4). Under the National Solar Mission (NSM), the renewable capacity targets are increased from 20 GW pre-Paris to 175 GW in the NDC document. The baseline scenario also includes a reduction of transmission and distribution (T&D) losses from 33% in 2000 to 15% through Restructured Accelerated Power Development and Reforms Programme (R-APDRP). Under the National Mission of Enhanced Energy Efficiency (NMEEE), specific targets have been introduced to about 480 industrial units for reducing their specific energy consumption under the Perform Achieve and Trade (PAT) scheme initiated pre-Paris (2013–2016), which continues to 2030 and beyond.^{40–44}

2.2.2. Deep Decarbonization Pathways (DDP) Scenario. The Deep Decarbonization Pathways (DDP) Scenario ratchets the ongoing policies and NDC targets to capture the pledge made by India at COP26 to shift toward net-zero emissions by 2070. This includes the targets below outlined in the Indian NDC as submitted in COP26.⁴¹ These pathways are further segregated into two scenario groups: one is a coal-intensive pathway with carbon capture and storage (DDP-CCS) and the other is a non-fossil fuel-based pathway promoting renewables (DDP-R). In these scenarios, all countries (including India) are assumed to implement ambitious climate policies aiming to meet the Paris Agreement goals of well-below 2 °C (and make efforts to below 1.5 °C) after 2030.^{45,46} In the AIM-Enduse India model, the country increases its climate policy ambition after 2030 with accelerated uptake of renewable energy in

energy supply and demand, energy efficiency improvements, increased electrification of end-uses (e.g., through the high uptake of electric vehicles in transport), larger biofuel blending, and sectoral measures.

The technology options include actions taken to control and reduce mercury emissions. The study explores end-of-pipe (EoP) technologies among the cheapest available technologies (CAT) and best available technologies (BAT), in addition to decarbonization technologies. The list of these technologies, cost, and mercury emission reduction efficiencies has been summarized in the Supporting Information (Table S3 and Table S4). Table 1 provides an overview of the scenario description based on the climate and technology policy options.

2.2.3. Alternative Scenarios. We explore nine scenarios, three without mercury control technologies (NDC, DDP-CCS, DDP-R), three with the cheapest available mercury control technologies (NDC_CAT, DDP-CCS_CAT, DDP-R_CAT) and three with the best available mercury control technologies (NDC_BAT, DDP-CCS_BAT, DDP-R_BAT). The ‘without end-of-pipe technology’ scenarios (NDC, DDP-CCS, and DDP-R) do not include mercury mitigation technologies. Mercury mitigation in these scenarios is achieved through reduction in fossil fuel combustion (decarbonization) through a combination of energy efficiency, fuel switch to alternative sources, and installing CCS. The ‘with cheapest end-of-pipe technology’ scenarios (NDC_CAT, DDP-CCS_CAT, and DDP-R_CAT) select the least expensive mercury mitigation technologies in addition to decarbonization measures. The ‘with best end-of-pipe technology’ scenarios (NDC_BAT, DDP-CCS_BAT, and DDP-R_BAT) select the combination best available technologies to reduce maximum feasible mercury reduction in addition to decarbonization measures.

2.2.4. Uncertainty Analysis. With respect to uncertainties, it can be categorized into three factors: scenario settings, parameter settings, and activity settings. In this study, we focus on the effects of model parameter uncertainty based on the mercury emission factors for different sectors and energy types to estimate the range with baseline NDC and DDP scenarios due to the availability of data. The IPCC approach 1 has been used to calculate uncertainty from emission factors which is a simple propagation method. We have not conducted sensitivity analysis based on technology and cost.⁴⁷

2.2.5. Normalization of Results. Normalization of results is used to scale the carbon dioxide emissions and mercury emissions to bring them to a common range to compare the data sets across years. This has been used to observe and compare the rate of reduction of carbon dioxide emissions compared with a decrease in mercury emissions.

3. RESULTS AND DISCUSSION

3.1. Carbon Dioxide and Mercury Emissions without Control Technologies. Figure 2 and Figure 3 present the energy profiles by sector (power and industry) and by fuel. Energy combustion in the power sector is the major contributor to CO₂ emissions, as well as mercury emissions. In the industry sector, both energy demand and industrial processes (especially in iron and steel, cement industry), ferrous and non-ferrous metal production contribute to CO₂ and mercury emissions. The main contributors of CO₂ emissions by fuel include coal, natural gas, and oil, while most mercury emissions are generated from burning or reduction of coal, gas, and biomass (pertaining to industrial

Table 1. Scenario Description Used in This Study

Climate options	Mercury mitigation options	Scenario name	Description
NDC	without end of pipe (mercury control) technologies	NDC	The scenario takes into consideration the ongoing decarbonization policies (regulations, economic instruments) under the NDC policy document without end-of-pipe solution for mercury mitigation.
	with cheapest available technologies	NDC_CAT	The scenario considers decarbonization policies under NDC, together with the cheapest available technology (CAT) options with end-of-pipe solution for mercury mitigation.
	with best available technologies	NDC_BAT	The scenario considers decarbonization policies under NDC, together with the best available technology (BAT) options with end-of-pipe solution for mercury mitigation.
DDP-Carbon Capture Storage (DDP-CCS)	without end of pipe (mercury control) technologies	DDP-CCS	The scenario takes into consideration the ongoing decarbonization policies (regulations, economic instruments) under the updated NDC policy document toward well below 2 °C, keeping coal intensive with CCS.
	with cheapest available technologies	DDP-CCS_CAT	The scenario considers coal-intensive deep decarbonization policies with CCS, together with CAT options with end-of-pipe solution for mercury mitigation.
	with best available technologies	DDP-CCS_BAT	The scenario considers coal-intensive deep decarbonization policies with CCS, together with BAT options with end-of-pipe solution for mercury mitigation.
DDP-Renewables (DDP-R)	without end of pipe (mercury control) technologies	DDP-R	The scenario takes into consideration the ongoing decarbonization policies (regulations, economic instruments) under the updated NDC policy document toward well below 2 °C, promoting more renewables.
	with cheapest available technologies	DDP-R_CAT	The scenario considers coal phase-down deep decarbonization policies, together with CAT options with end-of-pipe solution for mercury mitigation.
	with best available technologies	DDP-R_BAT	The scenario considers coal phase-down deep decarbonization policies, together with BAT options with end-of-pipe solution for mercury mitigation.

processes). The rate of coal demand has been estimated to decrease in the NDC scenario in 2070 at a CAGR of 0.8% in the power sector, while it increases by 1.1% in the industry sector. There is an increase in coal, biomass, and gas observed in the DDP-CCS scenario at a CAGR of 1.1%, 1.3%, and 2.5%, respectively. While in the DDP-R scenario, coal is observed to decrease at a CAGR of 6.4% and 0.8% in the power and industry sectors, respectively.

Figure 4 presents CO₂ emissions while Figure 5 presents subsequent mercury emissions without mercury control technologies, due to decarbonization pathways. In the NDC scenario without end-of-pipe technologies, CO₂ emissions rise from 2.4 Bt of CO₂ in 2020 to 2.8 BtCO₂ in 2030, peaking in 2050 and 3.1 BtCO₂ in 2070. Under the DDP-CCS scenario without end-of-pipe technologies, CO₂ emissions rise to 3 BtCO₂ in 2030, peaking in 2040 and then reducing to 2.2 BtCO₂ in 2070, which is still higher than the 2010 level. While in the DDP-R scenario without end-of-pipe technologies, CO₂ emissions rise to 2.4 BtCO₂ in 2030, peaking in 2030 and then reducing to 1.6 BtCO₂ in 2070, which becomes the same as the 2010 level. Consequently, mercury emissions rise from 136 tonnes of Hg (tHg) in 2020 to 161 tHg in 2030 and 188 tHg in 2070 under the NDC scenario. Under the DDP-CCS scenario, mercury emissions rise to 176 tHg in 2030, peaking in 2050 and then reducing to 192 tHg in 2070. While in the DDP-R scenario, mercury emissions rise to 161 tHg in 2030, peaking in 2040 and then reducing to 116 tHg in 2070. The peaking years and co-benefit reduction effects of mercury emissions due to decarbonization measures differ from the profiles of CO₂ emissions due to the difference of the major sources of mercury emissions.

By analysis of the impacts of emissions derived from the power sector, the share of CO₂ emissions is projected to decrease from 49% in 2020 to 47% in 2030 and further to around 42% in 2070 under the NDC scenario. Under the coal-intensive DDP-CCS scenario, the share of CO₂ emissions increases to 51% in 2030 and 53% in 2070. On the other hand, under the coal phase-down DDP-R scenario, the share of CO₂ emissions decreases to about 41% in 2030 and 14% in 2070. As for mercury emissions, the share is projected to decrease from 51% in 2020 to 43% in 2030 and further to around 37% in 2070 under the NDC scenario. The share of mercury emissions decreases to about 37–47% in 2030 and 10–42% in 2070 in the DDP scenarios. This projected decline of mercury emissions in the share of electricity-related emissions implies that power generation is easier to decarbonize due to transitions toward low- and/or zero-carbon technological options (for example, solar PV, wind onshore, small hydro, waste to energy), which are already cost-competitive with conventional fossil fuel thermal power plants.

By focusing on the share of industrial-related emissions from coal, the share of CO₂ emissions increases from 51% in 2020 to 53% in 2030 and to 58% in 2070 under the NDC scenario. On the other hand, the share of CO₂ emissions decreases to about 49% in 2030 and 47% in 2070 in the DDP-CCS scenario and decreases more to about 59% in 2030 and 86% in 2070 in the DDP-R scenario. As for mercury emissions, the share is estimated to increase from 49% in 2020 to 57% in 2030 and further to around 63% in 2070 under the NDC scenario. Consequently, the share of mercury emissions increases to about 53–63% in 2030 and 58–90% in 2070 in the DDP scenarios. This is due to the drastic decrease in the share of mercury emissions derived from the power sector combined

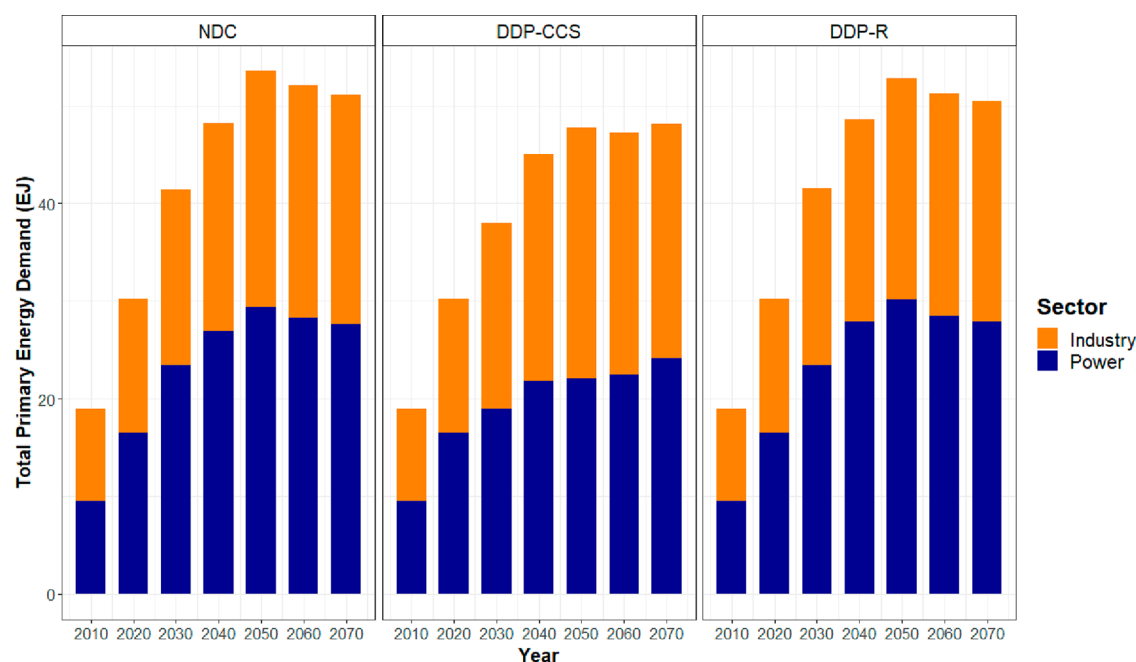


Figure 2. Total primary energy mix profile by fuel (power and industry) under NDC, DDP-CCS, and DDP-R scenarios.

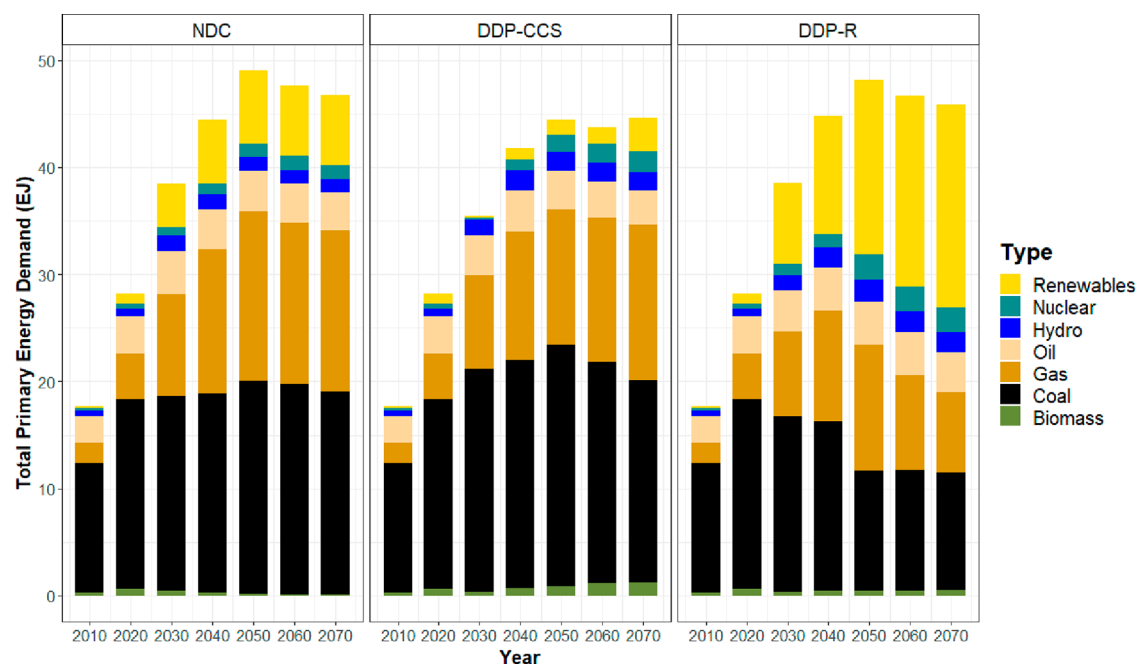


Figure 3. Total primary energy mix profile by sector (power and industry) under NDC, DDP-CCS, and DDP-R scenarios.

with limited options to reduce mercury emissions from energy-intensive industries that require high-temperature heat, which in the medium term will be provided by fossil fuels with limited potential for electrification. The decarbonization measures contribute to mercury mitigation through a combination of (a) energy efficiency in energy supply (power sector) and energy demand sectors (industry); (b) deployment of renewables; (c) demand reduction in the end-use sectors through dematerialization, and recycling; (d) deployment of CCS and (e) replacement of non-energy emissions due to switch to hydrogen and so on.

3.2. Mercury Emissions with End-of-Pipe Technologies. The Minamata Convention is aimed at protecting human

health and the environment from mercury, a global pollutant of major concern. Historical mercury emissions from 2004 to 2014 in India have been presented in the [Supporting Information](#) (SI). The main socio-economic drivers for mercury emissions in India are dependent on GDP composition, the fuel mixes in both power and industry sectors, and the industrial processes in the industry sectors. Coal combustion in both sectors is the major driver of not only carbon emissions but also mercury emissions. Additionally, in the industry sector, industrial processes such as reduction of ores in the iron and steel sector and carbonation of limestone in the cement industry are other drivers. Mercury emissions have increased at an annual growth rate of 8% between 2004

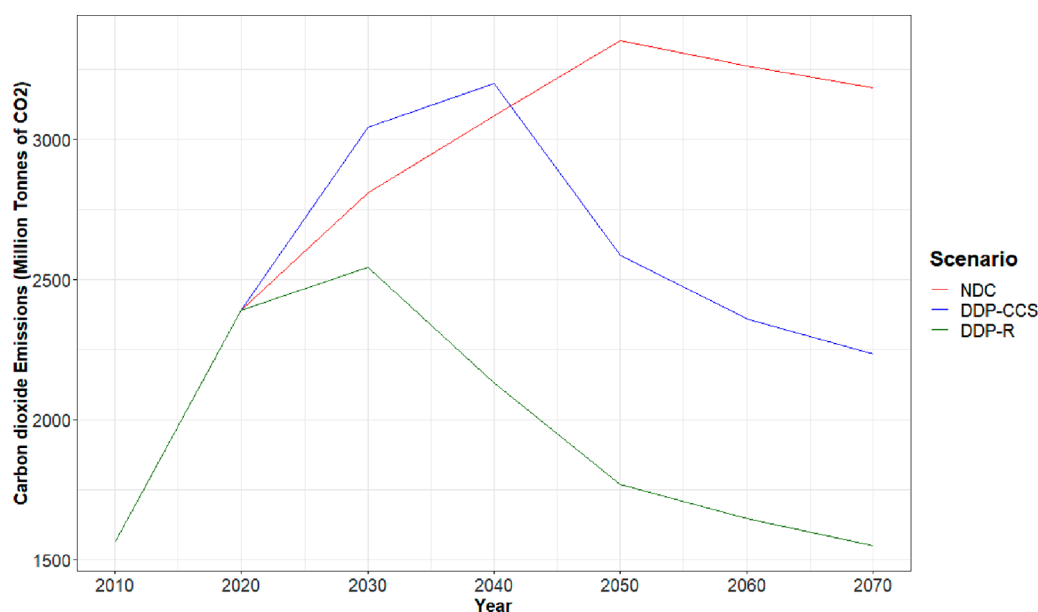


Figure 4. CO₂ emissions (million tonnes) (power and industry) under NDC, DDP-CCS, and DDP-R scenarios.

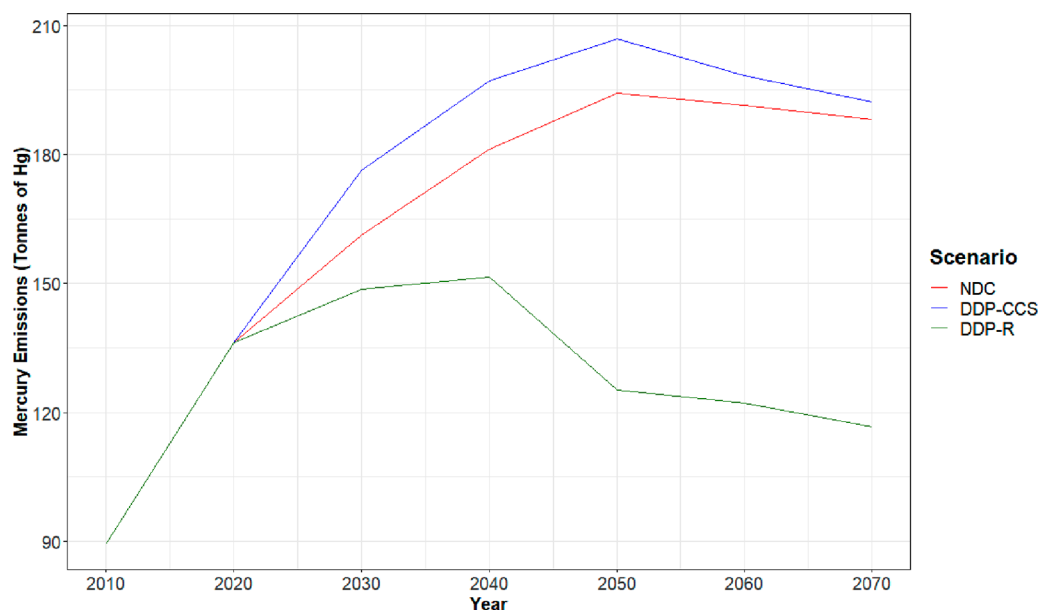


Figure 5. Mercury emissions (tonnes) (power and industry) under NDC, DDP-CCS, and DDP-R scenarios.

and 2014. The power and industry (energy consumption, industry processes, metal production) sector emissions amount to about 79% of the total mercury emissions in 2004, while the share decreased to 73% in 2014. The uncertainty between low and high emissions ranges between 55% and 75%.

Figure 6 illustrates total mercury projections under NDC and DDP scenarios in this study focusing on the power and industry sectors without and with end-of-pipe technologies, comparing impacts of cheapest available technologies (CAT) and best available technologies (BAT), whereas Figure 7 presents the mercury projections by sector under NDC and DDP scenarios. With CAT end-of-pipe technologies, mercury emissions are reduced by 4% in 2030, and 6% in 2070 in NDC-CAT when compared with the baseline NDC scenario without mercury mitigation technologies. In the DDP-CCS_CAT scenario, the mercury emissions are reduced by 12% in 2030,

and 15% in 2070 when compared with the baseline DDP-CCS scenario without mercury mitigation technologies. In the DDP-R_CAT scenario, the mercury emissions are reduced by 8% in 2030 and 10% in 2070 when compared with the baseline DDP-R scenario without mercury mitigation technologies. For the pathways installing BAT end-of-pipe technologies, mercury emissions are reduced by 7% in 2030, and 10% in 2070 in NDC-BAT when compared with the baseline NDC scenario without mercury mitigation technologies. In the DDP-CCS_BAT scenario, the mercury emissions are reduced by 29% in 2030, and 54% in 2070 when compared with the baseline DDP-CCS scenario without mercury mitigation technologies. In the DDP-R_BAT scenario, the mercury emissions are reduced by 34% in 2030, and 59% in 2070 when compared with the baseline DDP-R scenario without mercury mitigation technologies. Mercury emissions reduction

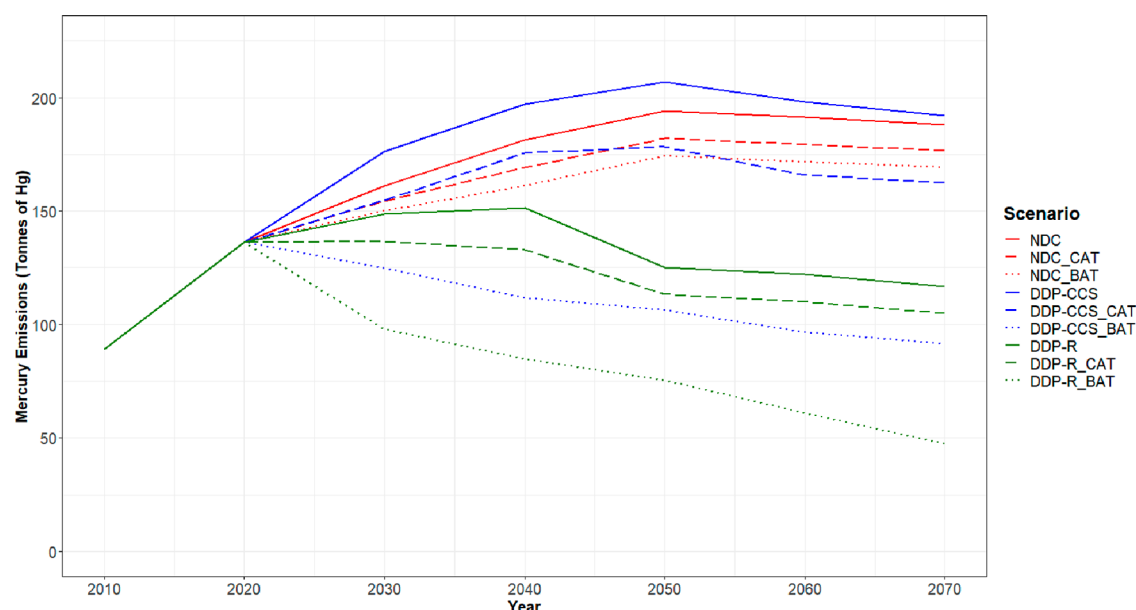


Figure 6. Mercury emission projections under NDC and DDP scenarios with end-of-pipe technologies from 2010 to 2070.

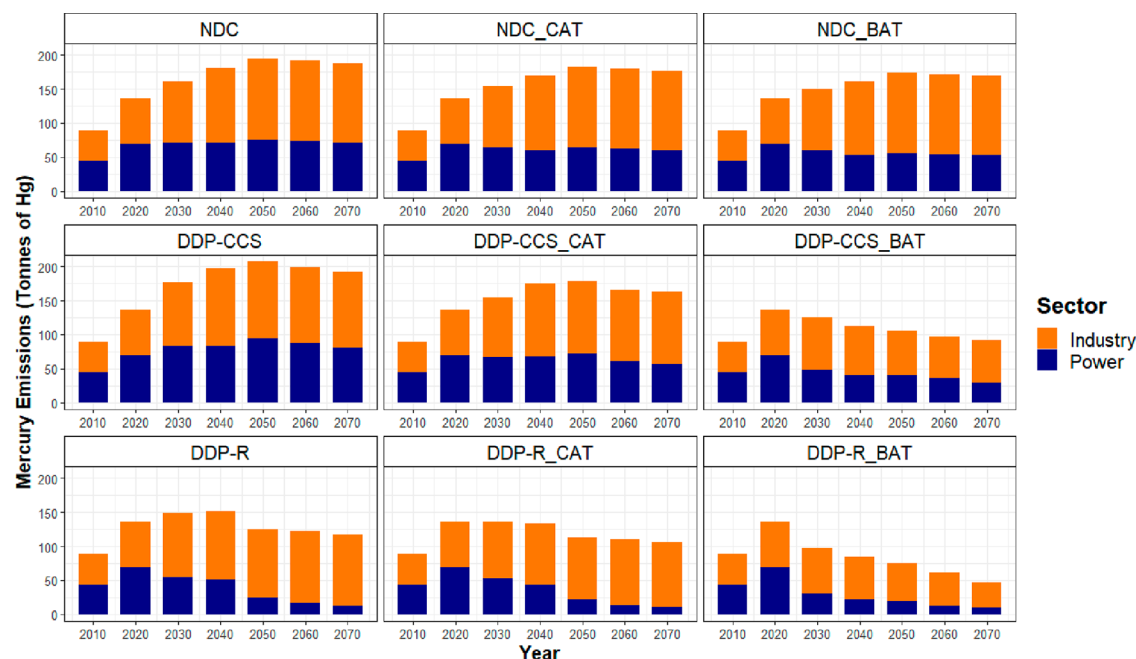


Figure 7. Mercury emission projections under NDC and DDP scenarios with end-of-pipe technologies in the power and industrial sectors from 2010 to 2070.

in the power sector is observed to be higher than those in the industry sector. The power sector especially in the DDP-R scenario does not require end-of-pipe technologies after 2050 by considering co-benefit mercury mitigation effects due to a drastic shift toward renewable technologies.

3.3. Co-benefits and Costs. Figure 8 illustrates the normalized CO_2 and normalized mercury emissions (2010 values are assumed to be (1) without mercury control technologies to compare and observe co-benefit impacts of decarbonization pathways on mitigation of mercury. In the NDC scenario, CO_2 and mercury emissions are increased by 80% and 81% in 2030, while they are increased by 104% and 111% in 2070 compared with the 2010 level. The rise in

emissions is due to the increased use of coal in both power and industry in the NDC scenario.

In the coal intensive scenario (DDP-CCS), CO_2 and mercury emissions are increased by 8.4% and 9.3% in 2030. CO_2 emissions are decreased by 29.9%, while the mercury emissions are increased by 2.2% in 2070 when compared with the NDC scenario. Compared to the NDC scenario, one can observe a rise in CO_2 emissions until 2030 and peak-out after 2030 due to the installation of CCS technologies; however, mercury emissions are more due to the increased coal use (energy penalty) required to use CCS technologies. Here, the implementation of end-of-pipe technologies is not taken into consideration.

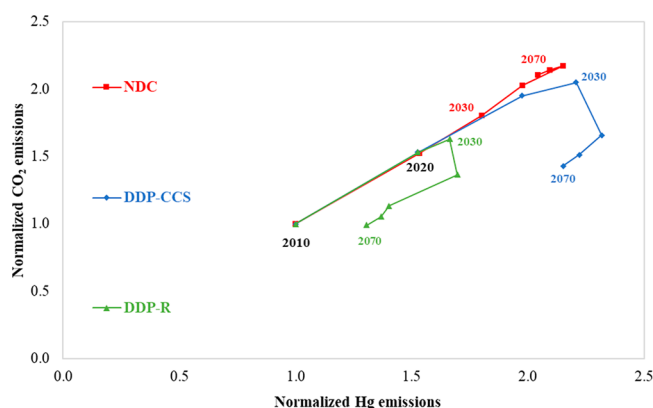


Figure 8. Correlation diagram between normalized CO₂ emission and normalized Hg emissions. Note: The 2010 values are assumed to be 1.

In the coal phase down scenario (DDP-R), CO₂ and mercury emissions are decreased by 9.5% and 7.9% in 2030, respectively. CO₂ emissions are significantly decreased by 51.4%, while mercury emissions are reduced by 38% in 2070 when compared with the NDC scenario. As the use of coal is reduced after 2030, one can observe a drastic decrease in both the level of CO₂ and mercury emissions. CO₂ emissions are observed to decline to 2010 levels; however, mercury emissions will not drop to 2010 levels because residual mercury emissions remain in the industry (processes and process use) sector. As in the DDP-CCS scenario, the implementation of end-of-pipe technologies is not taken into consideration.

Figure 9 presents the decrease in cumulative mercury emissions with the increase in corresponding system costs for additional mercury control end-of-pipe technologies (CAT and BAT) when compared with the NDC baseline scenario without end-of-pipe technologies between 2020 and 2070. The cumulative mercury emissions from 2020 to 2070 are observed to be reduced by 9%–27% in DDP_CAT scenarios when compared with the NDC scenario. This reduction improves the environment (i.e., air, subsequently water and soil) as well as human health. Using the cheapest available end-

of-pipe technologies (CAT), cumulative mercury emissions can be reduced by 21%–32% with an increase in corresponding system costs by 0.5% to 1%, while using best available end-of-pipe technologies (BAT), those emissions can be reduced by 47%–55% with increase in costs by 1.5% to 3% when compared with the baseline NDC scenario. According to our estimates, the cost of abatement in the industry sector including energy consumption, industrial processes, and metal production is three to nine times more than that in the power sector for best available technologies.

3.4. Impact of Uncertainties. Figure 10 displays the mercury emissions in the low, mid, and high ranges under NDC and DDP scenarios with end-of-pipe technologies in the power and industry sectors from 2010 to 2070. The uncertainty ranges of the fossil fuel type and reducing agents used are higher in the industry sector compared to those in the power sector. The information on the type of coal is highly uncertain in iron and steel, cement, and metal production. The overall range for mercury emissions in 2070 due to the uncertainty of the mercury emission factor varies between $\pm 45\%$ and 66% over the mid-range emissions.

3.5. Policy Implications. India will prioritize achieving economic development and decarbonization due to its commitment to a net zero target. This study examined air quality and clean environment from a co-benefits approach perspective, especially for the decarbonization scenarios. We have attempted to capture the current NDC policies, coal-intensive decarbonization (DDP-CCS) and coal phase-down decarbonization (DDP-R) pathways. Compared to the baseline NDC scenario, it is observed that the co-benefits in terms of mercury mitigation along with CO₂ reduction are higher in the DDP-R scenario than in the DDP-CCS scenario. In a coal-intensive scenario (DDP-CCS), India will need to invest in air pollution control technologies, along with decarbonization technologies to reduce mercury emissions. For the cheapest and best available end-of-pipe technologies (CAT and BAT), mercury mitigation is cost-effective for the power sector; however, a stronger policy framework with economic instruments and the relevant market mechanism will be required in the industry sector to reduce mercury emissions in the DDP

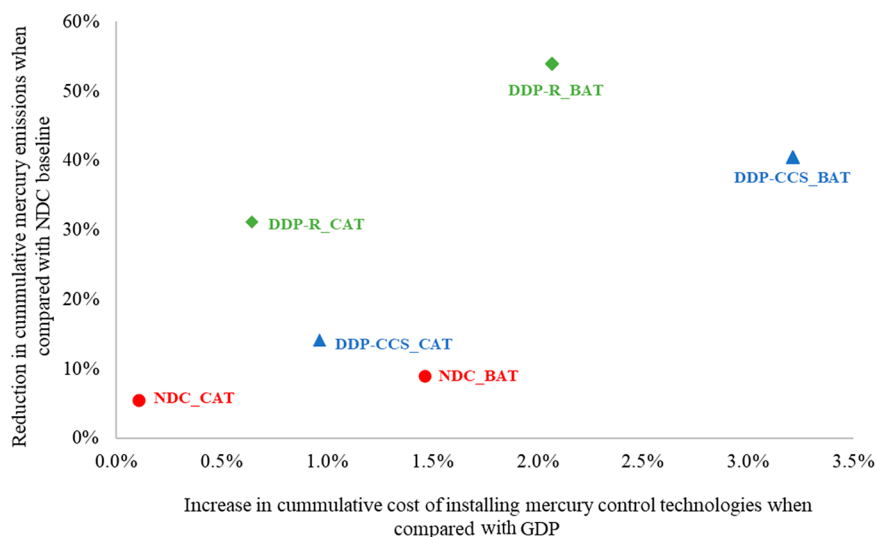


Figure 9. Decrease in cumulative mercury emissions compared with baseline NDC and incremental cost of mercury control technologies between 2020 and 2070.

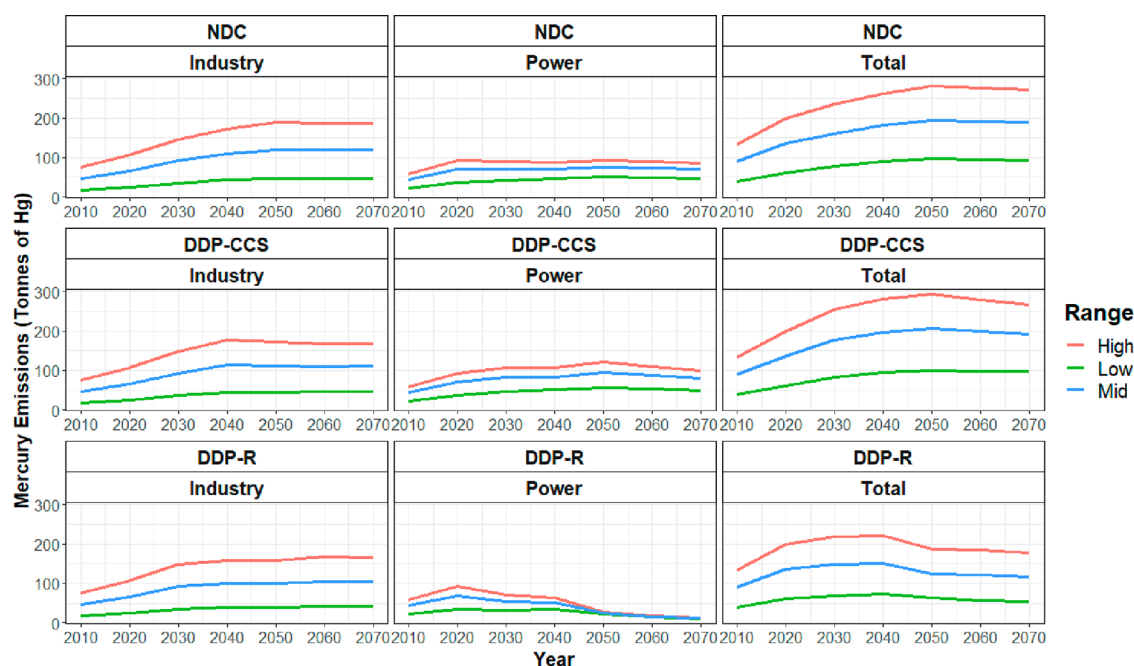


Figure 10. Mercury emission in the high, mid, and low range under NDC and DDP scenarios with end-of-pipe technologies in the power and industry sector from 2010 to 2070.

scenarios. Technology transfer and adaption with innovation will be required to reduce costs especially for mercury mitigation technologies to be installed in medium-, small-, and micro-scale industries.

The coal power plants are the largest mercury and carbon dioxide emitters. The mercury standards were introduced in 1981 under the Air Pollution and Control Act. These are comparable to WHO standards (0.03 mg/Nm^3). The study investigates the reduction of mercury emissions through decarbonization, carbon neutral policies, and implementation of the Minamata convention in the power and industry sectors. The emission norms were amended and mandated in 2017; however, they have surpassed the WHO norms due to an overall increase in India's energy supply and end-use activities.

The NDC, DDP-CCS, and DDP-R pathways without mercury control technologies in the power and industry sectors show a considerable decrease in the overall CO_2 and mercury mitigation. However, to achieve the standards mandated by the Indian Air Pollution and Control Act (amended), mandatory installations of the end-of-pipe technologies become essential to mitigate the emissions. The NDC_CAT, DDP-CCS_CAT, and DDP-R_CAT pathways present the emissions achieved by installing the cheapest available end-of-pipe technologies through national and sub-national market mechanisms. The Indian government recently green-lighted the creation of a carbon market under the Energy Conservation (Amendment) Bill 2022. Additionally, Gujarat (state) designed and developed the first particulate pollution market in 2019.

The Indian Ministry of Environment, Forest, and Climate Change (MoEFCC) should mandate a targeted significant reduction of mercury, especially from the industry sector. The NDC_BAT, DDP-CCS_BAT, and DDP-R_BAT pathways can be achieved only through the stringent implementation of mandatory policies through measurement, verification, and reporting. The industry sector needs to be incentivized in the form of a subsidy or rebate to install end-of-pipe technologies.

Innovative financial mechanisms will be required to make the best available technologies affordable for medium, small, and micro-enterprises.

The uncertainty analysis has been conducted to demonstrate the range of the net mercury emissions based on the energy source/reducing agent; however, the model cannot distinguish types of coal (domestic production versus import) for the power and industry sectors. Furthermore, in comparison to the power sector, majority ownership of the energy-intensive industry sector is privately owned. Hence, cost will play a significant role in the selection of technology for mercury mitigation and installing a combination of technology (advanced types such as ESP-FF) especially in the industry sector. The study currently does not include the cost and benefits of coal beneficiation as well as sensitivity analyses of technology costs. Further analysis is required to assess the local benefits to the environment in addition to the health and social benefits from the decarbonization and mercury mitigation pathways.

■ ASSOCIATED CONTENT

⑨ Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.3c01820>.

Model description with salient features, policy measures under different scenarios; calculations pertaining to uncertainty analysis and normalization, mercury content by sector; mercury control technologies; historical mercury emissions for reference (PDF)

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Notes

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ABBREVIATIONS

Bt, Billion tonnes
 BAT, Best available technologies
 CAT, Cheapest available technologies
 CCS, Carbon Capture and Storage
 CO₂, Carbon dioxide
 DDP, Deep Decarbonization Pathways
 EoP, End-of-Pipe
 GHG, Greenhouse gas
 Hg, Mercury
 MC, Minamata Convention
 MEA, Multilateral Environmental Agreements
 MoEFCC, Ministry of Environment, Forest, and Climate Change of India
 NAPCC, National Action Plan on Climate Change
 NDC, National Determined Contribution
 NH₃, Ammonia
 NMEEE, National Mission of Enhanced Energy Efficiency
 NMVOC, Non-Methane Volatile Organic Compounds
 NO_x, oxides of nitrogen
 NSM, National Solar Mission
 O₃, Ozone
 PAT, Perform Achieve and Trade
 PM₁₀, Particulate Matter (10 μm)
 PM_{2.5}, Particulate Matter (2.5 μm)
 R-APDRP, Restructured Accelerated Power Development and Reforms Programme
 R, Renewables
 UNEP, United Nations Environment Programme
 UNFCCC, United Nations Framework Convention on Climate Change
 SO₂, Sulfur dioxide
 SDG, Sustainable Development Goals

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