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Future $PM_{2.5}$ emissions from metal production to meet renewable energy demand

Sagar D Rathod[1], Tami C Bond[2], Zbigniew Klimont[3], Jeffrey R Pierce[1], Natalie Mahowald[4], Chaitri Roy[1,5], John Thompson[4,6], Ryan P Scott[7], Karin Olson Hoal[4] and Peter Rafaj[3,*]

[1] Department of Atmospheric Science, Colorado State University, Fort Collins, CO, United States of America
[2] Department of Mechanical Engineering, Colorado State University, Fort Collins, CO, United States of America
[3] International Institute for Applied Systems Analysis, Laxenburg, Austria
[4] Department of Earth and Atmospheric Science, Cornell University, Ithaca, NY, United States of America
[5] Indian Institute of Tropical Meteorology, Pune, Maharashtra, India
[6] PetraScience Consultants, Vancouver, BC, Canada
[7] Department of Political Science, Colorado State University, Fort Collins, CO, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: rafaj@iiasa.ac.at

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Abstract

A shift from fossil fuel to renewable energy is crucial in limiting global temperature increase to 2 °C above preindustrial levels. However, renewable energy technologies, solar photovoltaics, wind turbines, and electric vehicles are metal-intensive, and the mining and smelting processes to obtain the needed metals are emission-intensive. We estimate the future $PM_{2.5}$ emissions from mining and smelting to meet the metal demand of renewable energy technologies in two climate pathways to be 0.3–0.6 Tg yr^{-1} in the 2020–2050 period, which are projected to contribute 10%–30% of total anthropogenic primary $PM_{2.5}$ combustion emissions in many countries. The concentration of mineral reserves in a few regions means the impacts are also regionally concentrated. Rapid decarbonization could lead to a faster reduction of overall anthropogenic $PM_{2.5}$ emissions but also could create more unevenness in the distributions of emissions relative to where demand occurs. Options to reduce metal-related $PM_{2.5}$ emissions by over 90% exist and are well understood; introducing policy requiring their installation could avoid emission hotspots.

1. Introduction

Anthropogenic emissions of greenhouse gases (GHGs) from fossil fuel combustion are the largest drivers of anthropogenic climate change (Masson-Delmotte *et al* 2021). Projections of future global warming due to ongoing human activities suggest a temperature increase of 2 °C–6 °C compared to pre-industrial levels (Masson-Delmotte *et al* 2021). To limit this temperature increase, many countries have committed to reducing their GHG emissions by shifting their energy sources to renewable energy such as solar and wind ('The Paris Agreement, UNFCCC 2016').

More than 20 metals, including conventional and rare-earth, are required in the production of solar photovoltaic panels (PVs), wind turbines, and electric vehicles (EVs) (Giurco *et al* 2019, Watari *et al* 2019). The extraction and processing of these metals are emission-intensive activities causing health and ecosystem damages due to local and transboundary air pollution (Ghose and Majee 2001, Kavouras *et al* 2001, Csavina *et al* 2011). On a capacity basis (kg metal required per GW installed), the major renewable energy technologies require more than two orders of magnitude more metals than fossil fuel technologies (Valero *et al* 2018, Watari *et al* 2019). The metal demand to make the major renewable energy technologies might reach around 5–20 times the present-day production levels in 2050 (e.g. Giurco *et al* 2019).

Mining and smelting are two major processes needed to extract and refine metals. Both these processes are emission-intensive for air contaminants such as particulate matter and SO_2 (Dudka and Adriano 1997). Mining emissions occur during digging and extraction in open-pit mines, loading and unloading of trucks, storage and handling, and some initial ore refinement at source (cutting or crushing, wetting, etc) (Ghose and Majee 2001, Huertas *et al* 2012). Smelting emissions occur during high-temperature melting of metals to reduce impurities (generally in a blast furnace) and some secondary melting with high-grade oxygen to reach desired quality (generally in a basic oxygen furnace or in the presence of some electrolytes) (US EPA 2016). In terms of primary impacts, mining and smelting contribute to more than 10% of ambient $PM_{2.5}$ concentrations in industrial cities such as Santiago in Chile and Panzhihua in China (Jorquera and Barraza 2012, Xu *et al* 2021). Metal smelting is also a cause of heavy-metal pollution, such as mercury and nickel, in many places (Tian *et al* 2012, Wu *et al* 2012). There has been no estimation of future impacts on air quality from the processes to supply these materials in high renewable energy demand climate scenarios.

Only a few countries have economically feasible reserves and resources of many of these metals, and hence these countries control the metal supply (e.g. Giurco *et al* 2019). For example, the Bolivia–Argentina–Chile triangle has over 50% of known reserves of the lithium needed for batteries (Seefeldt 2020). Along with supplying the metals, these regions also bear the environmental impacts from mining and smelting (Kaunda 2020). The dependence on solar and wind for rapid decarbonization and the material intensity of these technologies and the subsequent environmental impacts create a complex problem: global decarbonization might create local pollution impacts (Mwaanga *et al* 2019, Lèbre *et al* 2020). Because of growing concerns around critical metal supply, countries might focus inwards for meeting the metal demand, either by increasing local extraction or acquiring raw ores from elsewhere (Vekasi 2021). The changing regionality of metal extraction and processing could lead to changes in where impacts might occur relative to demand (e.g. increased exploration in the Round Top Mountain, USA, Pingitore 2019).

This work aims at estimating the primary $PM_{2.5}$ emissions from mining and smelting of metals obtained specifically for making three technologies required to expand renewable energy: solar PV, wind turbines, and EVs. Many studies have estimated how trade redistributes emissions among countries for conventional goods and services (Lin *et al* 2014, Zhang *et al* 2017, Wu *et al* 2021). This work augments this body of literature, focusing on the capital equipment required to deploy renewable energy. We analyze the effect of metal production regionality on distributions of emissions relative to demand, and compare the effects of decarbonization rate and emission abatement on both emission totals and distributions. We also compare the projections with a highly idealized case in which each country produces metal to meet its own demands for renewable capacity. This extreme self-producing case is used mainly to contrast with emission distributions caused by natural trade.

2. Methods

We estimate the atmospheric emissions of primary $PM_{2.5}$ (particulate matter with diameter smaller than 2.5 μm) by multiplying activity and emission factors that consider extent of mitigation technology applied at specific location/region (Bond *et al* 2004, Klimont *et al* 2017). Activity is the driver that causes emissions, such as energy or amount of metal mined, e.g. kWh energy generated, and emission factor is the emission intensity of production process, e.g. g $PM_{2.5}$ kWh^{-1}. We use equations S1–S3 (available online at stacks.iop.org/ERL/17/044043/mmedia) (within text S1) to derive metal demand projections, map the metal demand to relevant GAINS (Greenhouse Gas—Air Pollution Interactions and Synergies, Klimont *et al* 2017) process sectors, and estimate emissions from each GAINS sector in different years, respectively. This paper illustrates the distribution of environmental impact using $PM_{2.5}$. A complete analysis of air pollution impacts would include SO_2, NO_x, volatile organic compounds, and organic precursors, among others. However, NOx and VOCs are less relevant for the sectors covered in this study in terms of $PM_{2.5}$ formation, therefore we focus on implications for primary $PM_{2.5}$. In particular, SO_2 would increase the atmospheric concentration of particulate matter, but an atmospheric model is required to estimate the yield of $PM_{2.5}$ from SO_2. A simplified modelling experiment comparing magnitudes of SO_2 emission among regions under different scenarios is not reported here, but gave similar findings about regional distribution of emission and the effect of abatement. The analysis is performed at the global scale for the years 2020–2050, with a five-year resolution. We analyze eight policies of decarbonization rates, abatement, and production regionality for their effect on emissions and distributions, as shown in table 1 and described below. The penetration of renewable energy is projected to reduce the dependency, and hence emissions, from fossil fuel combustion sources. We compare the metal production-related $PM_{2.5}$ emissions to anthropogenic combustion $PM_{2.5}$ emissions to evaluate its relative regional contribution. We use the anthropogenic combustion emissions from the GAINS model in the corresponding energy and abatement cases as described below.

2.1. Activity

Renewable additions (GW yr^{-1}) and fleet projections (vehicles yr^{-1}) are based on two scenarios from World Energy Outlook 2020 (International Energy Agency IEA 2020). The 'Current Energy Policies' scenario relies on projections in the IEA Stated Policies Scenario, which predicts energy mix based on

Table 1. Scenarios explored in this study. Two cases of each policy are explored, for a total of eight scenarios.

	Cases							
Scenarios	1	2	3	4	5	6	7	8
Energy Policy	→	→	→	→	↘	↘	↘	↘
Air Pollution Policy	→	→	↘	↘	→	→	↘	↘
Production Regionality	֍	●	֍	●	֍	●	֍	●

Energy Policy		*Air Pollution Policy*		*Production Regionality*	
Current Energy Policy	→	Current Abatement Legislation	→	Global Market	֍
Rapid Decarbonization	↘	Stringent Mitigation	↘	Local Production	●

current or committed policies. Anthropogenic GHG emissions in scenarios used in this study correspond approximately to a set of scenarios used in the climate modeling community within the IPCC sixth Assessment Report. These so called shared socioeconomic pathways (SSPs) span across different macroeconomic, population and climate policy assumptions (Riahi *et al* 2017). The Current Energy Policy scenario is similar to the SSP2-4.5 (Fricko *et al* 2017). The Rapid Decarbonization scenario corresponds to IEA's Sustainable Development Scenario. It assumes a much faster decarbonization rate than the Stated Policies Scenario and has anthropogenic GHG emissions similar to the SSP1-2.6 (van Vuuren *et al* 2017). The comparison of outcomes between the two scenarios demonstrates how metal demand, total anthropogenic emissions, total air pollution, and regional distributions of metal production may respond to rapid decarbonization. Metal composition and intensities from Watari *et al* (2019) are used for all three technologies (table S1) for the 2020–2050 period. We assume all solar PV to be crystalline silica PV and all wind turbines to be onshore based on their projected higher penetration in SSP scenarios (https://tntcat.iiasa.acat/SspDb), and all EVs to be passenger EV based on their projected number of sales compared to other forms of EVs, the relatively smaller difference in material requirement between vehicle types, and the uncertainty in future material composition and intensities (table S2, and Wolfram *et al* 2021). For the mining sector, the activity in units of kg of ore is estimated as the sum of the steel, aluminum, and all non-ferrous metals (NFMEs) multiplied by three (based on 2019 global steel-to-iron-ore and aluminum-to-bauxite production ratios) since the metal-to-ore data were scarce for most metals, and because many important critical metals are simply obtained as by-products during conventional metal production. IEA activity data are downscaled from the original 26 macro regions to 180 emission/source GAINS-regions using a downscaling routine described in SI text 2 (Rafaj *et al* 2018).

2.2. Emission factors

Region-specific uncontrolled $PM_{2.5}$ emission factors for both combustion and non-combustion activities are used from the GAINS model for metal mining and smelting sectors. Emission factors for the mining sector represent the emissions during digging and extraction. Fugitive emissions from mines and trucking related operations are not considered due to a lack of data. Smelting emission factors represent the particulate emissions during high-temperature melting of ores in blast furnaces for iron and aluminum. For NFMEs sector, we use emission factor for copper as it is the largest NFME considered in this work. Two GAINS abatement pathways, 'Current Abatement Legislation' in which abatement policies are based on current and stated policies, and 'Stringent Mitigation' in which the best control technologies are employed to the maximum extent without structurally changing the energy mix, are analyzed (Rafaj *et al* 2018). Most results presented here will be with Current Abatement Legislation, while Stringent Mitigation is used to assess the effect of stricter abatement policies on emissions. Under the Stringent Mitigation case, different regions adopt the best possible abatement measures starting from 2020 and peaking by 2040. Factors such as present stock of technologies and the technical feasibility of control application govern the abatement rate and penetration in different regions in the Stringent Mitigation case (Rafaj *et al* 2018).

2.3. Regionality of activity

To evaluate the effect of the location of production on emissions, we explore two cases, Global Market and Local Production. Under the Global Market scenario, the amount of renewables-related metal activity occurring in a region is proportional to the total metal activity in the IEA projections (International Energy Agency IEA 2020). IEA predicts the magnitude and regionality of metal production based on policies, infrastructure change, and economic projections. However, in the 'Global Market' regionality, only a few countries produce most minerals. This concentrates environmental impacts in the producing countries and creates a concentrated supply chain that is vulnerable to trade disruptions (Nassar *et al* 2020). We simulate an idealized 'Local Production' case in which countries mine and smelt their own metals for renewable energy devices. This scenario assumes that all countries have sufficient mineral resources and technologies to mine and smelt metal ores and metals. While this is an idealized scenario, countries may move in this direction to ensure mineral security (American Mineral Security Act 2020, European Commission 2020), and thus it could greatly affect where and how production happens. We use a distribution index, similar to the Gini index (Lorenz 1905, Gastwirth 1972), to quantitatively compare regional distributions of emissions to metal demand in different decarbonization, abatement, and production scenarios. The distribution index can be derived by plotting in Cartesian coordinates where the x-axis is the cumulative normalized metal demand from the lowest to the highest and the y-axis is the cumulative normalized emissions corresponding to the demand region. Then, the distribution index is calculated as the ratio of the area between the perfect equality line and the curve divided by the total area under the perfect equality line. A distribution index value closer to zero indicates emissions occur in demand region, and a value of one indicates most emissions are concentrated in fewer regions than demand.

3. Results and discussion

3.1. Metal demand

Under the Current Energy Policies scenario, the total finished metal demand is 195 million tons (Mt) yr^{-1} in 2020, peaking at 270 Mt yr^{-1} in years 2040–2045 and ending at 250 Mt yr^{-1} in 2050. Under the Rapid Decarbonization scenario, the total finished metal demand peaks at 480 Mt yr^{-1} in year 2040 and then declines to 325 Mt yr^{-1} in 2050 (figure S1, table S3). Among the renewable technologies, demand is dominated (around 70%) by solar in all years in both the scenarios (figure S1) due to its high metal intensity and the overall role in capacity addition. EVs pose around 20% of renewables-related metal demand in Current Energy Policies and 30% in Rapid Decarbonization. Total metal demand by wind turbines is the least, at around 1%–4% in both the scenarios. Iron and steel account for more than 90% of the total metal demand due to their higher intensity in all the three technologies (table S3). The metal demand by renewables represents about 8%–17% of all-use demand for steel, 10%–28% for NFMEs, and 4%–12% for aluminum (table S3).

Low- and middle-income countries represent most of the metal demand due to their projected renewable energy addition (International Energy Agency IEA 2020). India and China account for 20%–45% of the metal demand (figures S2–S4) via solar PVs, wind turbines, and EVs. High-income regions represent a major demand in the first half of the 2020–2050 period but then have slower growth, except for EVs for which growth is higher in the second half of the period (figures S2–S4). The relative metal demand is much higher from Asian, African, and Latin American countries in the Rapid Decarbonization than Current Energy Policies for all the three technologies, and Rapid Decarbonization in general has more regional diversity in demand than Current Energy Policies.

3.2. Emissions

Figures 1(a) and (b) show the regional $PM_{2.5}$ emissions from mining and smelting to meet the metal demand of global renewables in the two pathways with the Current Abatement Legislation measures. Emission values in the Rapid Decarbonization values are almost twice those of Current Energy Policies in many years for the Current Abatement Legislation case, similar to metal demand. India and China dominate emissions in both scenarios. USA, Russia, Eastern Europe, and rest-of-Asia account for about 30% of emissions. Rest-of-Asia, Africa, and South America have similar contribution to emission in the two scenarios, at about 15%. Stronger abatement in future years is projected to cause about 90% emission reduction in both the pathways (figure S5). Emissions peak at the same time as capacity addition in both the scenarios with Current Abatement Legislation. With Stringent Mitigation, emissions are projected to peak much earlier than with Current Abatement Legislation (figure S5), and with much lower magnitude (Klimont *et al* 2017, Rafaj *et al* 2018). Emissions remain at a constant minimum level after 2035 due to the offsetting effect of capacity addition and emission control (figure S5).

Technology-wise, solar photovoltaics and EVs cause most of the emissions in Current Energy Policies and Rapid Decarbonization with both Current Abatement Legislation and Stringent Mitigation (figure S6), similar to their fractions in the metal demand. Process-wise, smelting represents about 95% of total primary $PM_{2.5}$ emissions and mining the rest (figure S7). Steel, NFMEs, and aluminum smelting represent about 80%, 10%, and 5% of the total with similar contributions in Current Abatement Legislation and Stringent Mitigation cases. The relative contribution of mining is projected to increase even with Stringent Mitigation as controls are applied to point sources more than area sources (figure S7).

Figure 2 shows the anthropogenic combustion and metal-related primary $PM_{2.5}$ emissions and the contribution of mining and smelting to anthropogenic combustion emissions in the two scenarios. Primary $PM_{2.5}$ emissions from mining and smelting to meet global renewable energy demand are projected to reach 5%–15% of total anthropogenic combustion $PM_{2.5}$ emissions in India (figures 2(b)–(f)) and China (figures 2(a)–(e)) in both pathways with Current Abatement Legislation policies. North America and European Union (figures 2(c)–(g)) are projected to have a similar rate of emission reduction as India and China but the contribution by mining

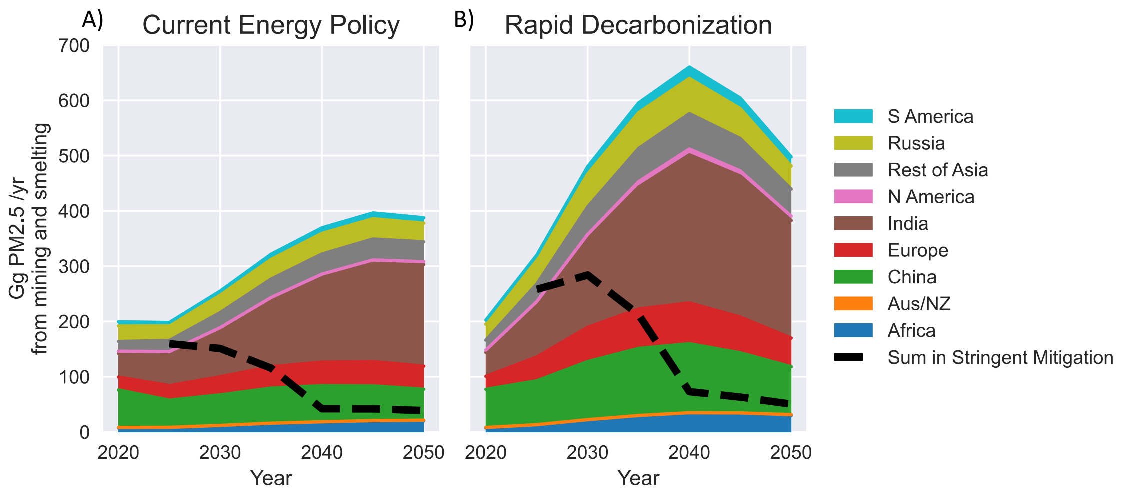

Figure 1. $PM_{2.5}$ emissions from metal mining and smelting toward making renewable energy devices in (a) Current Energy Policies and (b) Rapid Decarbonization scenarios by region with Current Abatement Legislation policies. Dashed lines show the total emissions for Stringent Mitigation cases. Note: no data available for stringent mitigation for the year 2020.

and smelting is much smaller, due to the lower expected future production and cleaner smelter plants. The $PM_{2.5}$ emission contribution due to mining and smelting is amplified in the Rapid Decarbonization scenario due more demand of metals and a quicker reduction of fossil fuel emission. However, even with higher metal-related emissions the total anthropogenic emissions are much lower in the Rapid Decarbonization scenario compared to Current Energy Policies.

The global shift from fossil to renewable energy is estimated to create a high burden of air pollution due to metal mining and smelting in many regions (figures S8–S10). Introducing available mitigation techniques, however, could reduce the burden by rapidly reducing emissions in most regions. After 2035, when penetration of abatement measures increases in the Stringent Mitigation case (Klimont *et al* 2017, Rafaj *et al* 2018), mining and smelting-related emissions decrease rapidly along with other combustion emissions. The contribution of mining and smelting emission falls from over 15% in India in the Current Abatement Legislation case to less than 5% after 2035. For regions such as Eastern Europe where mining and smelting emissions are projected to be dominant, the contribution of these emissions drops by half between Current Abatement Legislation and Stringent Mitigation cases, demonstrating the role of policies stimulating introduction of efficient emission mitigation technologies.

3.3. Regional distributions of metal demand, production, and emissions

Figures 3(a)–(c) show regional contributions to metal demand, production, and smelting-related $PM_{2.5}$ emissions in the two abatement scenarios for the Current Energy Policies and Rapid Decarbonization pathways for the year 2050, based on Global Market regionality. Figures 3(c) and (d) show the same information as figures 3(a) and (b), but for the Local Production case where all countries mine and smelt to meet their own renewable-driven metal demand. Figure 4 shows the timeseries of the distribution index for the cases studied in this work (data in table S4). A value of zero indicates the same distribution between emission and demand, and higher values indicate that emission is relatively more concentrated than demand. Below we discuss the effect of the rate of decarbonization, abatement, and production regionality on emissions and the distribution index.

3.3.1. Rate of decarbonization

With Current Abatement Legislation and Global Market regionality, the Current Energy Policies pathway has a lower distribution index compared to Rapid Decarbonization in the 2020–2050 period (figure 4), indicating a more evenly distributed regionality of emissions compared to demand. In Rapid Decarbonization, with Current Abatement Legislation and Global Market, more regions add renewable capacity, but the number of regions producing metals remains the same in the two pathways, so its overall distribution index becomes higher particularly in later years.

3.3.2. Abatement policy

Current Abatement Legislation cases have a much higher distribution index in future years compared to Stringent Mitigation cases for both the decarbonization pathways under the Global Market regionality (figure 4). Stringent Mitigation in this case leads to a lower distribution index because in this case abatement also occurs in regions with high-emitting technology. Most emissions occur in India if Current Abatement Legislations are considered, and in China if Stringent Mitigations are considered in the scenarios (figure 3). This difference between India and

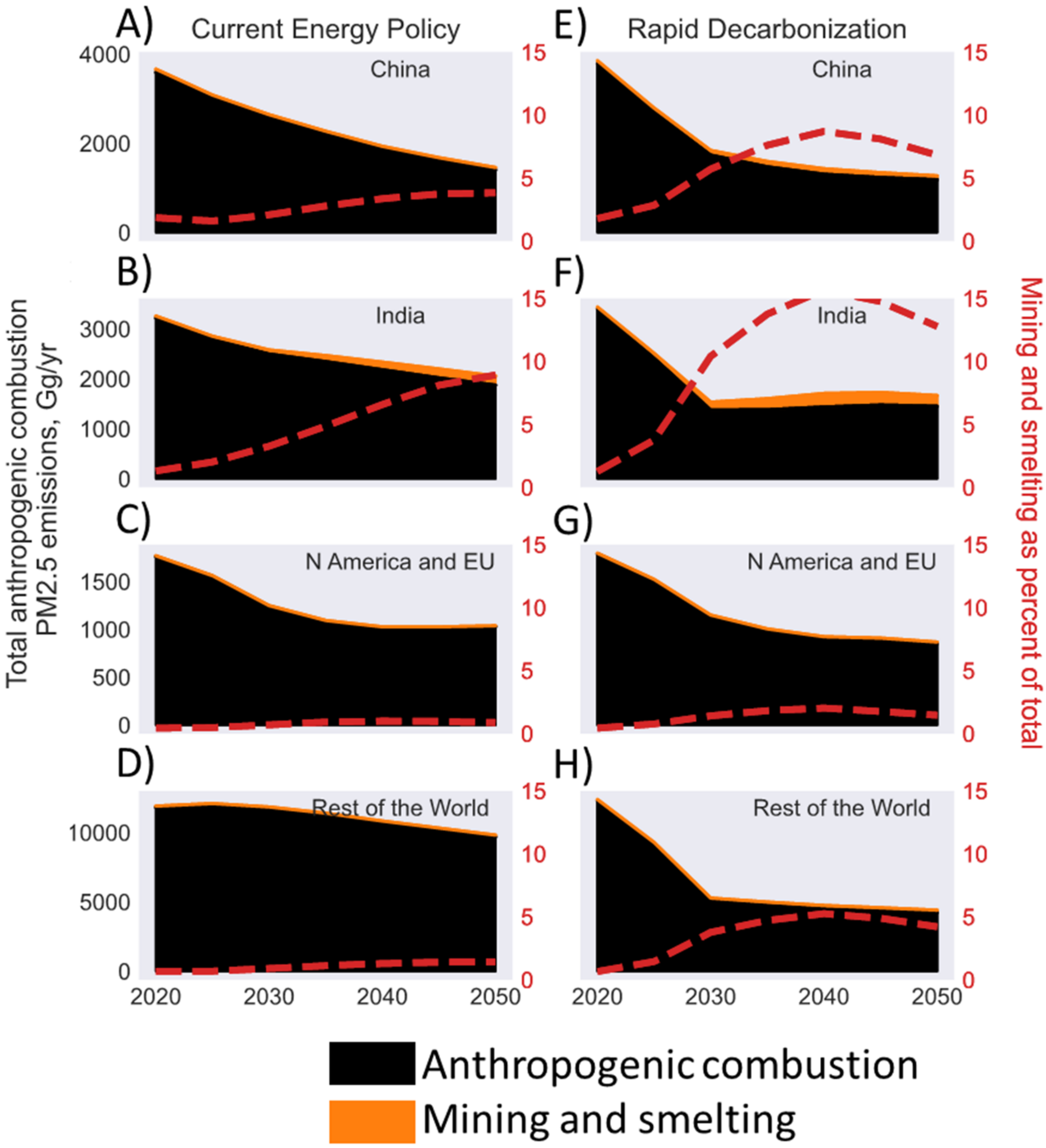

Figure 2. Absolute primary $PM_{2.5}$ emissions from anthropogenic combustion (black) and mining and smelting for metals for renewable technologies (orange) shown for the Current Energy Policies (a)–(d) and Rapid Decarbonization scenarios (e)–(h) for India, China, North America and European Union, and rest of the world. $PM_{2.5}$ emissions by mining and smelting to meet metal demand for renewables, shown as percent of total (mining and smelting and fossil fuel combustion) (red line, right axis).

China in the two scenarios is due to the assumed higher emission factor and lower abatement penetration in China compared to India for the smelting sector under Stringent Mitigation measures (Rafaj *et al* 2018).

3.3.3. Production regionality

Most future demand occurs in low- and middle-income regions. In the hypothetical Local Production case, production also occurs in regions where emission control policies are not stringent (figures 3(c) and (d)). Thus, metal-related emissions are higher in the Local Production cases than in Global Market for both, Current Energy Policies and Rapid Decarbonization (figure 4). Local Production cases have lower distribution index than Global Market under stated abatement policies (figure 4). This is because the regional distribution of emissions is roughly the same as demand in absence of strong controls. However, even when most regions reduce their emissions in the Stringent Mitigation case, highest emission occurs in regions that lag in abatement measures, skewing the regional distribution of emissions compared to demand and leading to a higher distribution index in the Local Production case with Stringent Mitigation.

3.4. Implications and caveats

The global metal-related $PM_{2.5}$ emissions of 0.3–0.6 Tg yr^{-1} to make renewable energy devices is a small fraction of total anthropogenic emissions, and

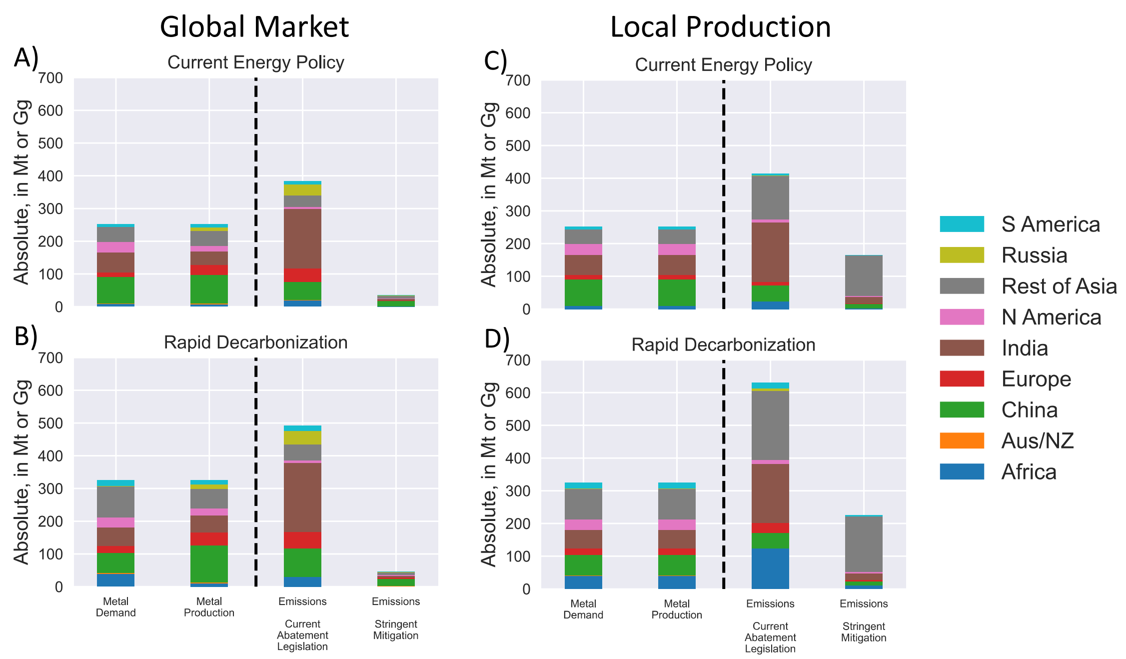

Figure 3. Absolute total metal demand (Mt), production (Mt), and related emissions (Gg) for Current Energy Policies (a)–(c) and Rapid Decarbonization (b)–(d) scenarios with Global Market regionality (a), (b), and with Local Production regionality (c), (d). Shown only for the year 2050.

Figure 4. Trends in distribution index for regional distributions of emissions relative to demand, for all cases. Dashed lines show current abatement legislation cases. Line widths and dash widths are linearly proportional to 2025–2050 total emissions from mining and smelting. The distribution index shows how regionally emissions are distributed compared to where demand occurs. A value closer to zero indicates emissions are collocated with demand. Values closer to one indicate most emissions are comparatively concentrated in fewer regions compared to demand. 'Current' under energy policy and abatement policy refers to 'Current Energy Policies' and 'Current Abatement Legislation', respectively.

it is also small compared to the expected decrease in combustion emissions. Thus, this emission increase is not expected to attract global attention, but atmospheric pollution in producing areas needs to be evaluated as part of the life cycle so that the global move to renewable energy does not unfairly burden a few regions.

The highly idealized Local Production scenario avoids the effective export of emissions caused by metal trade. However, the Local Production scenario would increase metal production and related pollution in these same areas where abatement measures are weak. Both global moves toward renewable energy and individual nations' attention to mineral security may increase demand for metals. Attention to emission abatement measures in the metal production sector, especially in regions with currently low abatement measures, is needed before these shifts occur; otherwise, nations may be forced into increasing security of energy or minerals at the expense of their inhabitants' health.

Several assumptions in this study affect the magnitude and regionality of metal demand, production, and emissions and are summarized here. We use present-day metal intensity values for 2020–2050, although compact devices or devices that use different materials (e.g. Das *et al* 2019) could affect future metal demand and activity location. IEA (2021) predicts increased material efficiency could reduce cobalt demand in EV battery by half but only modestly affect lithium demand. Advanced materials in solar panels have generally lower material requirement than the crystalline silica panels modeled in this study. As current mines run out of feasible and high-grade ores, economies might either shift production to newer, feasible mines and create new smelter plants near them, or produce more ore to get the same metal amount (e.g. Mohr *et al* 2015). The rate of ore quality decline could range from 0.1% to 5% per year (Northey *et al* 2014, Calvo *et al* 2016, Watari *et al* 2019) and hence could affect the amount of mining and the location of new mines. Materials for transmission and utility energy storage are not considered here, and might represent more than 30% of total renewables-related metal demand (IEA 2021). Finally, local production costs are affected by the accessibility of metal resources in each region, and the response of demand to this change in cost has not been modeled here.

Even if the assumptions listed above were further refined, the major lessons from this analysis are not expected to change. That is, rapid decarbonization will lead to a large overall decrease in $PM_{2.5}$ emissions, but it can increase inequity by placing the atmospheric burden in producing regions (e.g. Mohr *et al* 2015), and those inequities cannot be solved by self-producing without attention to emission abatement.

4. Summary and conclusion

A shift from fossil fuel to renewable energy is crucial in achieving climate targets. However, the higher material intensity of most renewable energy devices compared to fossil fuel technologies, and the emission-intensive methods to obtain those materials cause environmental impacts. This work quantifies the $PM_{2.5}$ emissions from mining and smelting due to the metal requirement for achieving the renewable energy goals in two IEA scenarios implemented in GAINS model: Current Energy Policies and Rapid Decarbonization. Global $PM_{2.5}$ emissions from mining and smelting are projected to reach about 15% of total anthropogenic combustion-related $PM_{2.5}$ emissions in many regions in the Current Energy Policies scenario, and about 30% in the Rapid Decarbonization scenario between 2020 and 2050. Only a few regions such as India and China might bear the burden of metal-related emissions due to the projected metal exploration and production in those regions and their relatively higher-emitting smelter plants. Introduction of legislation that relies on proven technology to reduce air pollutant emissions, anticipating global energy transition to renewables, would avoid increased pollution. Rapid Decarbonization scenario is estimated to lead to overall lower anthropogenic emissions even if the mining and smelting emissions increase but could also lead to an increased unevenness of the distribution of metal-related emissions relative to demand, as compared to Current Energy Policies. Stronger application of emission control policies could reduce metal-related emissions by 90% and also reduce the unevenness of the distribution of emissions relative to demand. Moving metals production to an expanded set of countries may cause excess $PM_{2.5}$ exposure. Policies that can provide access to rare-earth metals for developing economies may thus be important in achieving the full climate benefits of renewable energy technologies.

Data availability statement

The activity and emission data for steel, aluminum, and non-ferrous, non-aluminum metals required toward making solar PVs, wind turbines, and electric vehicles are available from GAINS v4 (https://gains.iiasa.acat/gains4/GOD/index.login). Please contact Peter Rafaj (rafaj@iiasa.acat) for access to scenarios named below:

RATHOD_WEO2020_<SCENARIONAME>_<ABATEMENT>_<TECHNAME>_ACTUA

Where SCENARIONAME = 'STEPS' corresponding to Current Energy Policies or 'SDS' corresponding to Rapid Decarbonization.

ABATEMENT = 'CLE' corresponding to Current Abatement Legislation or 'MFR' corresponding to Stringent Mitigation

TECHNAME = 'SL', 'WN', or 'EV', corresponding to Solar PV, wind turbines, and electric vehicles, respectively.

The data that support the findings of this study are available upon reasonable request from the authors.

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ORCID iDs

Sagar D Rathod https://orcid.org/0000-0001-7170-4302
Zbigniew Klimont https://orcid.org/0000-0003-2630-198X

Jeffrey R Pierce https://orcid.org/0000-0002-4241-838X
Natalie Mahowald https://orcid.org/0000-0002-2873-997X
Chaitri Roy https://orcid.org/0000-0002-8544-414X
Peter Rafaj https://orcid.org/0000-0003-1000-5617

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