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Calculating inter-sectoral carbon flows of a mining sector via hypothetical extraction method

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Abstract

Mining is among the oldest industries. It is the primary source of raw materials for most of the sectors. Little is known about the complex inter-sectoral carbon linkages of the mining industry. In this work, we estimate the inter- and intra-sectoral carbon linkage impacts of the mining sector across ten major economies by applying an input-output model, and the hypothetical extraction method and its modified version. The hypothetical extraction method removes an industrial block from an economic system, and afterwards, it makes a comparison between the before and after removal values. China with 195.47 Mt has the highest mining emissions, followed by USA, India, and Canada with 110.99 Mt, 108.79 Mt, and 76.92 Mt, respectively. The India's mining sector with 26.33 t/10^4 \$ is the most carbon-intensive, followed by Japan and Canada with 6.84 t/10^4 \$ and 5.22 t/10^4 \$, respectively. China's carbon emissions with -11.56% and -11.28%, respectively, have been affected the most by the total extraction of mining sector and forward carbon linkages, while for the backward carbon linkage, Canada with -1.33% has been affected the most. Canada has the highest mixed and internal emissions of 0.42 Mt and 47.88 Mt, respectively. However, China has the highest net-backward and net-forward emissions of 16.91 Mt and 189.22 Mt, respectively. For all nations, the mining sector is a net exporter of emissions to other industries. Based on the numerical findings, in this work, we discuss the mitigation measures for both the direct and indirect mining emissions.

1. Introduction

'Mining & Quarrying' is one of the oldest industries known to man. It is the basic source of raw materials for most of the production sectors. The industrial production process is based on the supply of minerals and metals [1]. Mining is also the main source of raw materials for the world fossil-based energy industry. Fossil fuel flames emitting carbon are the main cause of global warming [2]. The high environmental impact of the use of fossil fuel has pursued many nations to impose mechanisms for the decrease in the consumption of fossil fuels [3]. Despite this, fossil fuel will remain the main energy for decades to come. As per Exxon Mobil: The Outlook for Energy [4] in 2040: about 1/3 of the world energy will be delivered by oil, and from 2014-2040, about 40% of the world energy demand will be satisfied by natural gas, making it the most significant growing energy source. Thus as long as there is production and energy use, the mining sector will remain the primary source of raw material spplies.

The literature on the carbon & GHG emissions in the mining sector is summarized in the following.

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Category	Studies
Regional emissions	[5-7]
Climate change	[8, 9]
Driving factors	[10, 11]
Toxic emissions	[12, 13]
Haulers, transportation, and supply-chain	[14-18]
Fugitive emissions	[19-22]
Blasting & explosives	[23, 24]
Pollutants	[25, 26]
Ecological and sustainable mining	[27-33]
Health	[34-39]
Energy	[40-42]
Mine aging	[43]
Emission control, carbon capture, and stock	[44-47]
Social sciences	[48]

The literature generally focuses on the direct industrial emissions, while it mostly ignores the inter-industrial carbon relations [49]. An industry's connection with rest through direct and indirect intermediate inputs and outputs defines sectoral linkages [50]. We can broadly define sectoral linkages under four main groups. The traditional multiplier was first suggested by [51], whereby they proposed direct input coefficients matrix Column or Row sums for calculation of backward or forward linkages[1]. Rasmussen [52] has suggested the row sum of Leontief inverse as a measure of the forward links. Jones [53]; Miller & Blair [54], Miller & Lahr [55], and Beyers [56] criticized their approach as an incorrect measure, and suggested the row sum of Ghosh model for forward linkage measurements. Thus classical multiplier is the column sum of Leontief inverse matrix for backward and row aggregate of Ghosh matrix for forward linkage [57]. The classical multiplier approach has been applied to study the industrial ties including environmental [58] and carbon linkages [57, 59, 60].

The other three methods used for measuring industrial linkages are ground upon the hypothetical extraction model (HEM). As per Wang *et al.* [49] HEM (hypothetical extraction method) mimics a sectors' importance by deleting all linkages of the sector instead of calculating its significance based on just technical factor plain averages. Classical multiplier fails to report the relative size of the sector's impact [61]. Original Strassert [62] HEM removes all the internal and external linkages related to a sector and measures its extraction impact on the economy. The Original HEM fails to distinguish between the forward and backward linkage measures [63]. Cella [64] has proposed an alternative for calculation of the total linkage; he developed the model as a response to Schultz [65] and Meller & Marfán [66]. According to Cella, both of them have either 'underestimated' or 'overestimated' the total linkages. Furthermore, he decomposed the total linkage into the forward and backward linkages. The total linkage measurement under Cella's [64] proposal is the same as the original, except that a sector's internal linkage is not removed. Duarte *et al.* [67] have introduced decomposition of inter-industrial links under MHEM (Modified hypothetical extraction model), which is more or less a further disintegration of the Cella's [64] proposal. Originally, the Cella's and modified HEM have been extensively used to describe industrial linkages and environmental problems in different setups including Water [67, 68], Industrial carbon linkages [49, 69-73], Energy [74], Building [75], Food production [76], Air pollutants [77, 78] and Household carbon linkages [79-83].

This work is novel in several ways. First of all, not much work has been done utilizing HEM and MHEM to understand the carbon linkage impact of the mining sector. Secondly, there is little work done on the across-country carbon linkage analysis of this sector. In this work, we not only have employed HEM and MHEM to study the complex carbon linkages of the mining sector, but also have used these models in a cross-country analysis of ten significant economies of the world. It will help us understand the impact of the mining sector on carbon linkages not only within these economies but also identify the country-specific mining sector ranking across these nations. A comprehensive analysis of mining industry carbon

[1]- An upstream inter-linkage of a sector with selling or input providing sectors is known as the backward linkage, whereas a downstream inter-linkage of a sector with purchasing or to whom it supplies its output is the forward linkage [57, 53].

linkages will tell us about the total, downstream, and upstream effects of the respective countries' mining sector on their national CO_2 emissions. It can help devise a mitigation policy based on the inter- and intra-sectoral root causes of mining discharges.

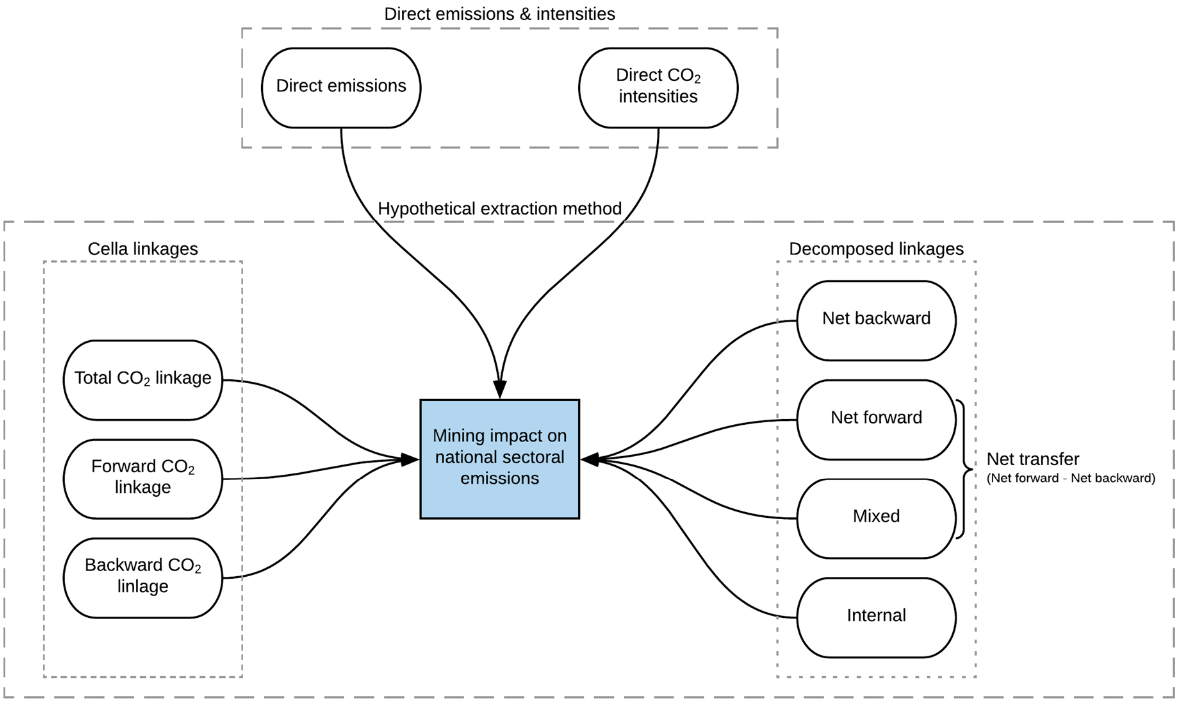

Figure 1. Framework for estimation of the mining sector's impact on nation wise industrial CO_2 emissions.

2. Methodology

2.1. Mining total carbon emissions and intensities

The Leontief model or the Leontief quantity model [55, 84] was first introduced by Wassily W. Leontief [85] as:

$$X = AX + Y \quad (1)$$

Isolation of X will give us:

$$X = \left(I - A\right)^{-1} Y \quad (2)$$

where the Total yield or output vector of a given economy is presented by X, I represents an $n \times n$ dimensioned identity matrix, A is a technology matrix whose element $a_{ij} = \frac{x_{ij}}{xj}$ represents the amount of the total output required from sector i to produce one unit at sector j, $(I - A)^{-1}$ represents the Leontief inverse matrix denoted as L, and Y is a vector of the final demand [86]; where any change in the final demand will cause a change in the output, while the input coefficients are constant. Here, by A, we mean domestic intermediate matrix excluding intermediate imports. If E^r represent the total energy and non-energy related carbon emissions for a given economy $r(r = 1,2,3\ldots,r)$ then the direct emission intensity for economy r is defined as the ratio of E^r to the total output of that economy X^r.

$$\gamma^r = \frac{E^r}{X^r} \quad (3)$$

where γ^r represents the direct emission intensity of economy r.

The total carbon emissions of economy r can be obtained by multiplying the diagonalized direct emission intensity γ^r by X^r.

$$E^r = \gamma^r \left(I - A^r\right)^{-1} Y^r \quad (4)$$

2.2. Hypothetical extraction method (HEM) for mining carbon linkage analysis

This method extracts a sector in an imaginary scenario from the original economic system, and makes a comparison between the initial system including this sector and the imaginary economy excluding the sector [70, 74]. Strassert [62] first introduced HEM. Schultz [65] used HEM to study an industry's economic effect; it was later modified by Cella [64] and Clements [87].

We can classify the entire economy by two blocks: block number one representing the mining sector of a given economy r as β^r_m, and block two β^r_{-m} representing all the other sectors in the given economy except for the mining sector. The resulting economy β can be presented as:

$$\beta^r = \begin{bmatrix} \beta^r_{m,m} & \beta^r_{m,-m} \\ \beta^r_{-m,m} & \beta^r_{-m,-m} \end{bmatrix} \tag{5}$$

The total carbon emissions of a given economy r can be presented as:

$$E^r = \begin{bmatrix} E^r_m \\ E^r_{-m} \end{bmatrix} = \begin{bmatrix} \gamma^r_m & 0 \\ 0 & \gamma^r_{-m} \end{bmatrix} \begin{bmatrix} X^r_m \\ X^r_{-m} \end{bmatrix} = \begin{bmatrix} \gamma^r_m & 0 \\ 0 & \gamma^r_{-m} \end{bmatrix} \left(\begin{bmatrix} A^r_{m,m} & A^r_{m,-m} \\ A^r_{-m,m} & A^r_{-m,-m} \end{bmatrix} \begin{bmatrix} X^r_m \\ X^r_{-m} \end{bmatrix} \begin{bmatrix} Y^r_m \\ Y^r_{-m} \end{bmatrix} \right) = \begin{bmatrix} \gamma^r_m & 0 \\ 0 & \gamma^r_{-m} \end{bmatrix} \begin{bmatrix} \varphi^r_{m,m} & \varphi^r_{m,-m} \\ \varphi^r_{-m,m} & \varphi^r_{-m,-m} \end{bmatrix} \begin{bmatrix} Y^r_m \\ Y^r_{-m} \end{bmatrix} \tag{6}$$

where the column vector $E^r = \begin{bmatrix} E^r_m \\ E^r_{-m} \end{bmatrix}$ represents the total emissions of a given economy, the direct emission intensity of a country r for the mining sector, and the rest of the economy is presented by $\begin{bmatrix} \gamma^r_m & 0 \\ 0 & \gamma^r_m \end{bmatrix}$; here, $\begin{bmatrix} X^r_m \\ X^r_{-m} \end{bmatrix}$ represents the total Output of the economy β^r and $\begin{bmatrix} Y^r_m \\ Y^r_{-m} \end{bmatrix}$ represents the final demand; $\begin{bmatrix} A^r_{m,m} & A^r_{m,-m} \\ A^r_{-m,m} & A^r_{-m,-m} \end{bmatrix}$ is the technology matrix of country r, and the Leontief inverse matrix is equal to $(I-A)^{-1} = \begin{bmatrix} \varphi^r_{m,m} & \varphi^r_{m,-m} \\ \varphi^r_{-m,m} & \varphi^r_{-m,-m} \end{bmatrix}$.

In the Cella's imaginary economy, there are no inputs to and no outputs from the mining sector to other sectors of the economy. Hence, there are no carbon emissions from the mining sector (except for the internal linkage), while the final demand of the respective country remains unchanged.

$$\overline{E}^r = \begin{bmatrix} \overline{E}^r_m \\ \overline{E}^r_{-m} \end{bmatrix} = \begin{bmatrix} \gamma^r_m & 0 \\ 0 & \gamma^r_{-m} \end{bmatrix} \left(\begin{bmatrix} A^r_{m,m} & 0 \\ 0 & A^r_{-m,-m} \end{bmatrix} \begin{bmatrix} X^r_m \\ X^r_{-m} \end{bmatrix} \begin{bmatrix} Y^r_m \\ Y^r_{-m} \end{bmatrix} \right) = \begin{bmatrix} \gamma^r_m & 0 \\ 0 & \gamma^r_{-m} \end{bmatrix} \begin{bmatrix} (I-A^r_{m,m})^{-1} & 0 \\ 0 & (I-A^r_{-m,-m})^{-1} \end{bmatrix} \begin{bmatrix} Y^r_m \\ Y^r_{-m} \end{bmatrix} \tag{7}$$

Following the equation presents the impact of the mining sector removal as:

$$E^r - \overline{E}^r = \begin{bmatrix} E^r_m - \overline{E}^r_m \\ E^r_{-m} - \overline{E}^r_{-m} \end{bmatrix} = \begin{bmatrix} \gamma^r_m & 0 \\ 0 & \gamma^r_{-m} \end{bmatrix} \begin{bmatrix} \varphi^r_{m,m} - (I-A^r_{m,m})^{-1} & 0 \\ 0 & \varphi^r_{-m,-m} - (I-A^r_{-m,-m})^{-1} \end{bmatrix} \begin{bmatrix} Y^r_m \\ Y^r_{-m} \end{bmatrix} = \begin{bmatrix} \Delta^r_{m,m} & \Delta^r_{m,-m} \\ \Delta^r_{-m,m} & \Delta^r_{-m,-m} \end{bmatrix} \begin{bmatrix} Y^r_m \\ Y^r_{-m} \end{bmatrix} \tag{8}$$

The subsequent equation exemplifies the impact of the mining sector's total link extraction due to a change in production on carbon emissions:

$$TL^r = \begin{bmatrix} E^r_m - \overline{E}^r_m \\ E^r_{-m} - \overline{E}^r_{-m} \end{bmatrix} \tag{9}$$

where TL^r represents the Cella total linkage for country r, and $\hat{u}$ denotes an appropriate unit vector $(\hat{\mu} = 1,1,\ldots,1)$. Cella further decomposed this total linkage into the backward and forward linkages, which can be presented as:

$$BL^r = \hat{\mu}\gamma^r_m \left[\varphi^r_{m,m} - (I - A^r_{m,m})^{-1} \right] Y^r_m + \hat{\mu}\gamma^r_{-m} \left[\varphi^r_{-m,m} \right] Y^r_m \tag{10}$$

where BL^r represents the Cella backward linkage of the mining sector for country r.

$$FL^r = \hat{\mu}\gamma^r_m \left[\varphi^r_{m,-m} \right] Y^r_{-m} + \hat{\mu}\gamma^r_{-m} \left[\varphi^r_{-m,-m} - (I - A^r_{-m,-m})^{-1} \right] Y^r_{-m} \tag{11}$$

where FL^r represents the Cella forward linkage of the mining sector for country r.

Normalization of the results can help us better comprehend the mining sector impact on a country's CO_2 emissions. One favourite way is to divide the absolute results by pre-extraction output value multiplied by 100. The resulting index presents 'economic-wide' reduction in output [55]. Song *et al.*[75] normalized the construction sector's extraction impact in a cross-country setup. Ali [70] and Zhang *et al.* [79] employed this normalized index to the CO_2 emission problem. Normally, a value greater than one indicates that the sector has a considerable impact on a country's carbon emissions. The following equations present the normalized total, forward, and backward links:

$$NTL^r = \frac{TL^r}{E^r} \times 100 \quad (12)$$

$$NBL^r = \frac{BL^r}{E^r} \times 100 \quad (13)$$

$$NFL^r = \frac{FL^r}{E^r} \times 100 \quad (14)$$

where NTL^r, NBL_r^r and, NFL^r represent the normalized indices of Cella total, backward, and forward carbon linkages for the mining sector of country r . Following Zhang *et al.* [79] for a better understanding of this article uses a negative sign to represent the % impact of the mining sector extraction from a specific economy r .

2.3. Modified hypothetical extraction model (MHEM)

Duarte *et al.* [67] further decomposed Cella's model for the Spanish water problem with four classifications, namely the internal, mixed, net forward, and net backward linkages. Internal emissions are CO_2 releases from in-house demand of a sector. Mixed emissions are from those goods that are initially produced by the target block (in our case, mining sector), then sold out, and eventually, purchased back (repurchased). Emissions from net backward link are from inter-sectoral imports of the target sector or group. Finally, emissions from the net forward links are from the carbon exports of the target sector to other industries or blocks.

Internal emissions:

$$IE^r = \hat{\mu}\gamma_m^r \left[(I - A_{m,m}^r)^{-1} \right] Y_m^r \quad (15)$$

where IE^r represents the internal emissions of the mining sector for country r .

Mixed emissions:

$$ME^r = \hat{\mu}\gamma_m^r \left[\varphi_{m,m}^r - (I - A_{m,m}^r)^{-1} \right] Y_m^r \quad (16)$$

where ME^r represents the mixed emissions of the mining sector for country r .

Net backward emissions:

$$NBE^r = \hat{\mu}\gamma_{-m}^r \left[\varphi_{-m,m}^r \right] Y_m^r \quad (17)$$

where NBE^r represents the net backward emissions of the mining sector for country r .

Net forward emissions:

$$NFE^r = \hat{\mu}\gamma_m^r \left[\varphi_{m,-m}^r \right] Y_{-m}^r \quad (18)$$

where NFE^r represents the net forward emissions of the mining sector for country r .

Target block net transferred carbon emissions can be presented by:

$$NTE^r = NFE^r - NBE^r \quad (19)$$

where NTE^r represents the net transferred emissions of the target block. A value greater than zero represents that positive emissions are being transferred by the block. A negative value represents the opposite, while a value equal to zero represents an equilibrium between the target block's carbon emissions and economy [69].

3. Data sources

The primary source of our data including IO tables and environmental accounts is from the world input-output database [88]. There are two releases, 2013 and 2016. Since the 2016 version lacks environmental accounts, we selected the 2013 release with the latest available data of the year 2009. Although the 2013 release provides IO tables for 2010 & 2011, it lacks environmental reports for the respective years. We utilized the 2013 releases' environmental accounts [89] and national IO tables [90, 91] for the year 2009. WIOD database presents the mining sector's input-output data and environmental accounts under the head of 'Mining & Quarrying.' Under release 2013, the following sub-categories are available: 'World, national, & regional IO tables,' 'environmental accounts,' and 'socio-economic information.' Many scholars have considered WIOD as a reliable source of information for environmental problems [3, 92-96].

4. Results

4.1. Total carbon emissions and direct carbon intensity

The direct emission intensities and total carbon emissions for the country-specific mining sectors could have using Equations (3) and (4). Figure 2 contains the spatial presentation of the top ten economies 'Mining & Quarrying[2]' total carbon emissions (Mt) during 2009. China with 195.47

[2]- 'Mining & Quarrying' has also been referred to as Mining sector in this paper.

Mt has the highest emissions of all ten world top economies, followed by the USA with 110.99 Mt. Third on the list with a marginal difference is India, having 108.79 Mt of carbon emissions. Canada, Japan, United Kingdom, and Brazil with 76.92 Mt, 22.05 Mt, 20.81 Mt, and 17.12 Mt, respectively, are the fourth, fifth, sixth, and seventh. Economically prominent nations of Germany 5 Mt, France 1.88 Mt, and Italy 1.05 Mt, all from EU, did not have high carbon emissions from 'Mining & Quarrying' during 2009.

Figure 3 contains the spatial presentation of 'Mining & Quarrying' direct carbon intensities (t/10^4 dollar) of the world top 10 economies for 2009. India with an alarmingly high direct emission intensity of 26.33 t/10^4 \$ topped the list. The Indian mining industry suffers from outdated technology & techniques, lack of proper infrastructure facilities, low innovation, lack of R&D, etc. [97]. These alongside with fossil fuel dependence are the main factors driving this alarmingly high carbon intensity of the Indian mining industry. Indian government alongside with Indian miners and their respective associations should take the necessary measures to reduce this high intensity, which is not only a threat to the current Indian environment but also with the future growth of the India's 'Mining & Quarrying' industry, this hazard will multiply. Japan with 6.84 t/10^4 \$ is the second and Canada with 5.22 t/10^4 \$ is the third, followed by China, Germany, UK, USA, Brazil, and France with 4.19 t/10^4 \$, 3.60 t/10^4 \$, 3.34 t/10^4 \$, 3.18 t/10^4 \$, 2.62 t/10^4 \$, and 2.01 t/10^4 \$ of carbon intensities, respectively. Italy with 0.92 t/10^4 \$ has the least carbon-intensive 'Mining & Quarrying' sector.

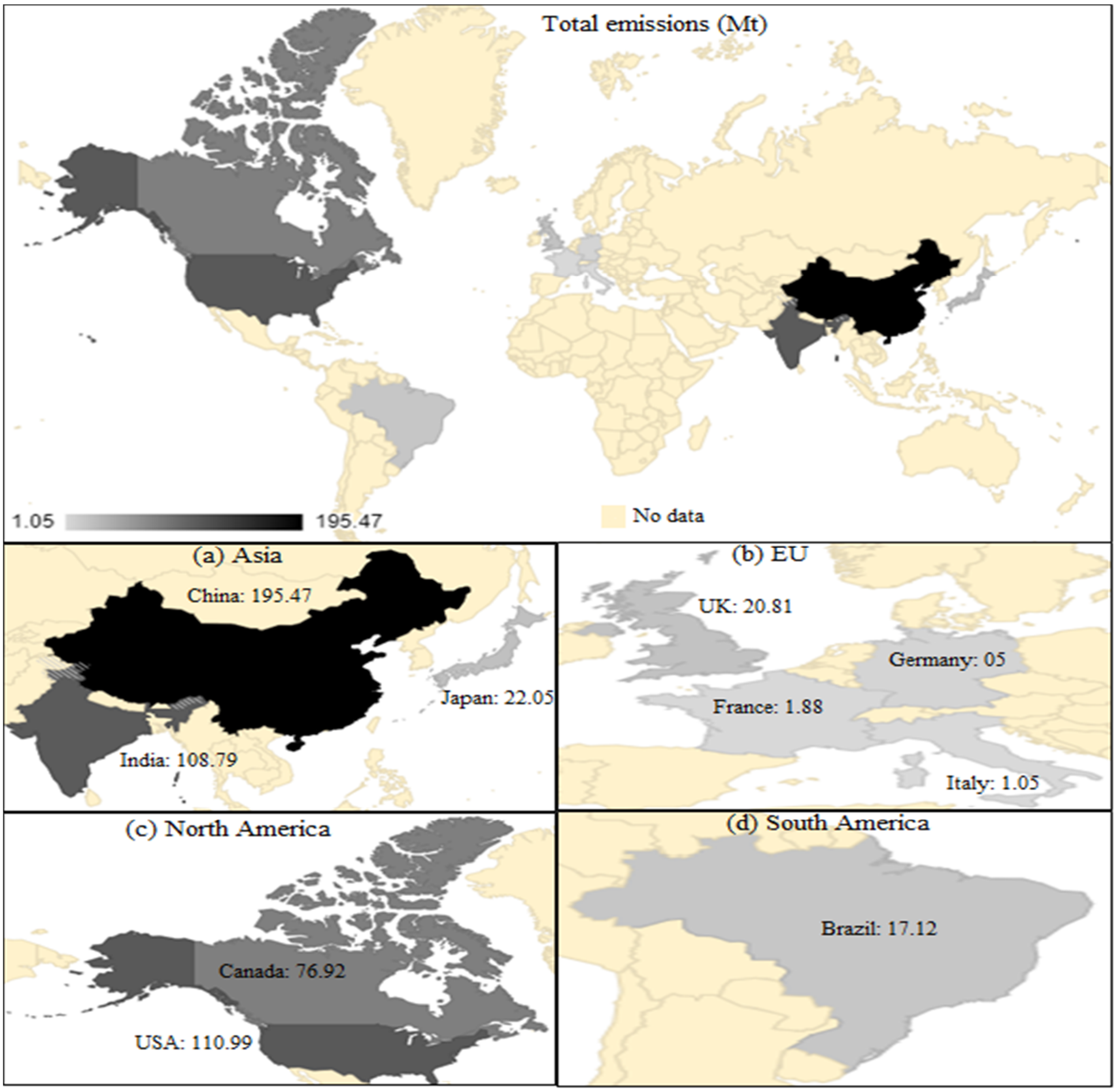

Figure 2. Spatial presentation of country wise total mining emissions.

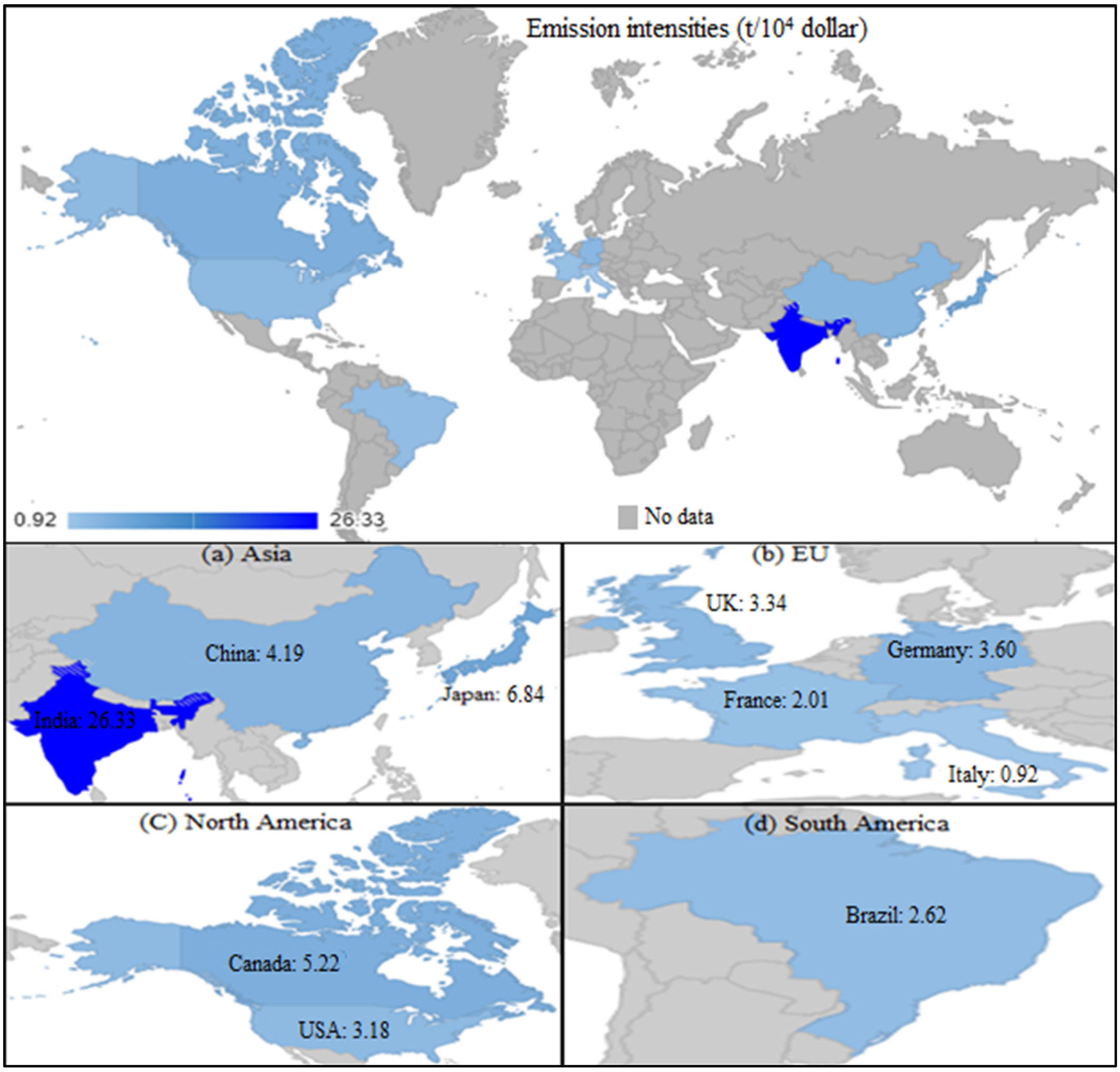

Figure 3. Spatial presentation of country wise mining emission intensities.

4.2. Mining carbon linkages

The absolute value indices of the total, backward, and forward linkages for country-specific mining sectors could have using Equations (9, 10) and (11). Table 1 contains the details. China's mining sector with 718.07 Mt, 17.28 Mt, and 700.80 Mt has the highest valued mining sector total, forward, and backward carbon linkages. USA's 'Mining & Quarrying' sector has the second highest total, forward, and backward links of 112.29 Mt, 13.92 Mt, and 98.38 Mt, respectively. India with total, backward, and forward carbon linkages of 97.75 Mt, 7.51 Mt, and 90.24 Mt is the third on the list. Canada with 37.68 Mt, 5.84 Mt, and 31.84 Mt for the total, backward, and forward carbon ties is the fourth. Japan has a total carbon linkage of 31.31 Mt; due to relatively large negative accounting 'changes in inventory' for 2009, it has a negative backward linkage of -1.04 Mt, which means that Inventory stock of Japanese economy has decreased from the 2008 levels. A negative change in the inventory balance shows that there has been no accounting increase to the current year inventory; instead, some part of the last year inventory has been used to satisfy the demand that should be credited from the current emissions. In this case, the small negative balance of Japan's backward linkage has reduced emissions from its total carbon linkage by a small margin. Owing to the negative backward linkage, Japan's mining sector forward carbon linkage (32.34 Mt) is higher than its total link. France has the smallest total and forward carbon linkages of 2.05 Mt and 1.85 Mt, respectively. Higher values of forward linkages over backward linkages indicate that for all the ten countries, the mining sector is mainly an exporter of emissions to other industries rather than an importer or absorber of emissions from other sectors.

Table 1. Countrywise carbon linkages of the mining sector.

Country	Absolute indices (Mt)			% Normalized indices		
	TL^r	BL^r	FL^r	NTL^r	NBL^r	NFL^r
USA	112.29	13.92	98.38	-2.68	-0.33	-2.35
China	718.07	17.28	700.80	-11.56	-0.28	-11.28
Japan	31.31	-1.04	32.34	-3.28	+0.11	-3.39
Germany	4.45	1.41	3.04	-0.70	-0.22	-0.48
UK	14.54	1.61	12.93	-3.44	-0.38	-3.06
India	97.75	7.51	90.24	-6.51	-0.50	-6.01
France	2.05	0.19	1.85	-0.79	-0.07	-0.71
Italy	2.11	0.12	1.99	-0.68	-0.04	-0.64
Canada	37.68	5.84	31.84	-8.58	-1.33	-7.25
Brazil	16.48	2.40	14.09	-6.56	-0.95	-5.61

Normalized indices explain the relative impact of the mining sector's extraction on a particular country's total carbon emissions. Out of the ten countries, hypothetical extraction of mining sector from the respective economies has affected China the most with -11.56% reduction in total emissions of China. Since the mining sector plays a key role in Chinese total carbon emissions mix, the Chinese government, to reduce its total emissions, should give importance to the mining sector in its mitigation plans and policies. Mining sector's extraction from the Canadian economy would cause a reduction of -8.58% towards total emissions. Brazil with a reduction of -6.56% to CO_2 emissions would be the third most affected nation in case of theoretical extraction of mining sector from its economy. Other nations who had a more than -1% reduction to their CO_2 emissions in case of imaginary extraction of mining sectors were India (-6.51%), UK (-3.44%), Japan (-3.28%), and USA (-2.68%), respectively. Only Canada had a significant Cella backward linkage impact of -1.33%. China with -11.28% had the highest forward linkage impact of the mining sector's extraction, followed by Canada with -7.25%. Other countries with significant Cella forward linkage impacts were India (-6.01%), Brazil (-5.61%), Japan (-3.39%), UK (-3.06%), and USA (-2.35%), respectively.

Table 2 contains a summary of the countries' comparative TL, BL, and FL rankings under the absolute and normalized indices. China's mining sector is ranked first in terms of its absolute value of total, backward, and forward carbon linkages. It means that China's mining sector has the highest value of these carbon linkages across the world's top ten economies. The normalized value of China's TL and FL carbon linkages is also the highest, while the normalized value of its backward linkage is at the sixth place across the top ten economies. It shows that the extraction of the China's mining sector backward linkage has a relatively less impact on the direct carbon emissions of Chinese economy as compared to its total and forward impacts.

Table 2. Countrywise ranking of carbon linkages for the mining sector.

Country	Absolute rank			Normalized rank		
	TL^r	BL^r	FL^r	NTL^r	NBL^r	NFL^r
USA	2	2	2	7	5	7
China	**1**	**1**	**1**	**1**	6	**1**
Japan	5	10	4	6	10	5
Germany	8	7	8	9	7	10
UK	7	6	7	5	4	6
India	3	3	3	4	3	3
France	10	8	10	8	8	8
Italy	9	9	9	10	9	9
Canada	4	4	5	2	**1**	2
Brazil	6	5	6	3	2	4

4.3. Decomposition of mining sector's carbon emissions

The internal emissions for country-specific mining sectors could have using Equation (15). Table 3 contains the details of countrywide disintegration of the mining sector carbon emissions. By intra-sectoral carbon emissions, we mean emissions from supply and demand of the mining sector products use within the industry. Mining sector of Canada not only has the highest internal emissions (47.88 Mt), it is the only country out of the ten nations whose IE value is higher than its net backward (5.43 Mt) and net forward emissions (28.62 Mt), which means that the Canadian government and miners, to mitigate their mining sector emissions, should focus on emissions arising from production (extraction) and consumption of products within the sector as compared to emissions from its imports (NBE) and exports (NFE). USA has the second highest internal emissions of 38.20 Mt, followed by India, UK, and Brazil with 33.94 Mt, 9.63 Mt and 6.52 Mt, respectively.

The mixed emissions for country-specific mining sectors could have using Equation (16). Mixed emissions are initially sold by the mining sector to other blocks/sectors of the economy and then purchased back. After Canada (0.42 Mt), China with 0.36 Mt has the second highest mixed emissions. India follows them with 0.30 Mt. USA and Brazil with 0.24 Mt and 0.12 Mt are the fourth and fifth, respectively. Overall, mixed emissions from the mining sector of all ten countries are not significant and the respective governments and miners might not have to pay much attention to their mining sector mixed emissions while planning for mitigation and reduction of mining emissions.

The net backwards and net forward emissions for country-specific mining sectors could have using Equations (17) and (18). China has the highest net backward (16.91 Mt) and net forward (189.22 Mt) mining sector emissions of all the nations under consideration. Other states with top mining sector net CO_2 purchases are USA (13.68 Mt), India (7.21 Mt), Canada (5.43 Mt), and Brazil (2.28 Mt), respectively. After China, India (74.55 Mt), USA (72.55 Mt), Canada (28.62 Mt), Japan (26.49 Mt), UK (11.13 Mt), and Brazil (10.49 Mt) has comparatively significant net forward carbon emissions. Overall, countries' mining sector net forward emissions are far more than emissions from net backward linkages, which means that the mining sector of the respective countries is a significant exporter of CO_2 emissions to other blocks/sectors of their respective economies.

The net transferred emissions for country-specific mining sectors could have using Equation (19). A positive value will indicate that the mining sector of the individual nation has a positive balance, i.e. it is absorbing less from other blocks/sectors and exporting more to other blocks/sectors. A negative balance will indicate that the mining sector of a specific country is absorbing (importing) more from and emitting (exporting) less to other blocks/sectors, while a value of zero will indicate that the sector emissions are in equilibrium. The mining sectors of all countries under consideration with positive balances are net exporters (emitters) of carbon emissions. China's mining sector with 172.30 Mt topped the list of countries under discussion. India's mining sector with 67.35 Mt is the second. USA's mining sector with net emissions of 58.88 Mt is the third. It is followed by Japan (27.47 Mt), Canada (23.20 Mt), and the UK (9.57 Mt), respectively.

Table 3. Countrywise decomposition of carbon linkages for the mining sector.

Country	IE^r	ME^r	NBE^r	NFE^r	NTE^r
USA	38.20	0.24	13.68	72.55	58.88
China	5.89	0.36	16.91	189.22	172.30
Japan	-4.38	-0.06	-0.98	26.49	27.47
Germany	2.94	0.00	1.40	2.06	0.66
UK	9.63	0.05	1.57	11.13	9.57
India	33.94	0.30	7.21	74.55	67.35
France	0.53	0.00	0.19	1.36	1.17
Italy	0.11	0.00	0.12	0.95	0.83
Canada	47.88	0.42	5.43	28.62	23.20
Brazil	6.52	0.12	2.28	10.49	8.21

5. Policy suggestions

Countrywise empirical analysis of mining emissions, intensities, inter-sectoral carbon linkages, and decomposition of carbon linkages enabled us to develop a deep understanding of the corresponding countries' mining sector environmental impact. Based on the knowledge acquired from our study, we propose the following policy suggestions for the policymakers and miners across the board.

1) Countries with comparatively high direct mining emission intensities like India, Japan, and Canada can learn from the experience of the least carbon-intensive mining industries from countries like Italy. Learn from their policies and mechanisms and devise mitigation policies of their own accordingly.

2) Hypothetical extraction of mining sector from economies like China, Canada, Brazil, and India would significantly reduce their total carbon emissions. This indicates the importance of the mining sector in the overall mix of carbon emissions for these countries. These countries, to reduce their total carbon emissions, should pay a keen attention to their respective mining sectors CO_2 releases.

3) For most of the economies, their net forward emissions are the most significant. Canada and Germany are an exception; their mining sector's internal carbon emissions are more than net backward and net forward carbon emissions. For these two nations mining carbon mitigation, special attention should be paid to their internal consumption scale and direct carbon intensity.

4) Empirical analysis of net transfer emissions (NT) from the mining sector of respective countries indicates that all states individual mining sectors are net emitters (exporters) rather than absorbers (importers) of carbon emissions. This means that the mining sector of these countries holds special responsibility towards the environment. Different policy instruments like carbon capping, carbon taxation, and pricing can be employed to promote a cleaner environment.

5) Focus towards innovation in the mining sector should be a part of the mitigation policy. For that, cooperation should be enhanced between these top ten world economies. Knowledge should flow freely, and countries should learn from each other's mitigation experiences.

6) All countries under discussion have net emitting (exporting) mining sectors. An effort should be made on the part of government and mining associations/agencies to reduce carbon intensity, which could be partially achieved through improved technology, i.e. fuel-efficient mining machinery and equipment and better techniques for blasting, drilling, etc. but mainly through less reliance on fossil fuel-based energy sources. For that, alternative energy sources should be considered at different stages of 'Mining and Quarrying.'

7) Finally, where possible, carbon capture should be introduced to reduce direct emissions from the sector of mining. Carbon captured can later be sold to other industries for the production of various products requiring CO_2 or stored underground at depleting fuel extraction sites; it could, to some extent, cover the cost of employment of carbon capture technology.

6. Conclusions

In this work, we have measured and analyzed the total emissions, direct carbon intensity, total, forward, and backward carbon linkages under Cella proposal and carbon linkage decomposition into internal, mixed, backward, and forward emissions of the 'Mining and Quarrying' sector of the world top 10 economies including USA, China, Japan, Germany, United Kingdom, India, Brazil, France, Italy, and Canada, respectively. The data was based upon the world input-output database for the year 2009. The main points are concluded as follow:

1) Of all the ten nations, China's mining sector had the highest total carbon emissions of 195.47 Mt. India had the highest mining sector direct emission intensity of 26.33 t/10^4 dollar. Italy with 0.92 (t/10^4 dollar) had the least carbon-intensive mining sector of all economies. China's mining sector had the highest absolute total carbon linkage of 718.07 Mt. Mining sector of China also had the highest backward (17.28 Mt) and forward (700.80 Mt) carbon linkages.

2) Decomposition of carbon linkages helps us understand the root causes of these emissions. Canada had the highest internal emissions (IE) of 47.80 Mt. No country had any significant mixed emissions (ME). For the mining sector's net backward emissions (NBEs), China with 16.91 Mt was number one. For net forward emissions, again China with 189.22 Mt topped the list. Net emissions tell us whether a specific sector of a country is net emitter (net exporter) to other sectors or a net absorber (importer) of emissions from those sectors. All countries mining sectors lead by China with 172.30 Mt were net exporters of carbon emissions.

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Calculating inter-sectoral carbon flows of a mining sector via hypothetical extraction method

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Abstract:

Mining is among the oldest industries. It is the primary source of raw materials for most of the sectors. Little is known about the complex inter-sectoral carbon linkages of the mining industry. In this work, we estimate the inter- and intra-sectoral carbon linkage impacts of the mining sector across ten major economies by applying an input-output model, and the hypothetical extraction method and its modified version. The hypothetical extraction method removes an industrial block from an economic system, and afterwards, it makes a comparison between the before and after removal values. China with 195.47 Mt has the highest mining emissions, followed by USA, India, and Canada with 110.99 Mt, 108.79 Mt, and 76.92 Mt, respectively. The India's mining sector with 26.33 t/10^4 \$ is the most carbon-intensive, followed by Japan and Canada with 6.84 t/10^4 \$ and 5.22 t/10^4 \$, respectively. China's carbon emissions with -11.56% and -11.28%, respectively, have been affected the most by the total extraction of mining sector and forward carbon linkages, while for the backward carbon linkage, Canada with -1.33% has been affected the most. Canada has the highest mixed and internal emissions of 0.42 Mt and 47.88 Mt, respectively. However, China has the highest net-backward and net-forward emissions of 16.91 Mt and 189.22 Mt, respectively. For all nations, the mining sector is a net exporter of emissions to other industries. Based on the numerical findings, in this work, we discuss the mitigation measures for both the direct and indirect mining emissions.

Keywords: Environment, Mining and Quarrying, Carbon Emissions, Input-Output Model, Hypothetical Extraction Model.