The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1756-8692.htm

Sectoral carbon linkages of Indian economy based on hypothetical extraction model

Muhammad Jawad Sajid
School of Management, Xuzhou University of Technology, Xuzhou, China

Qingren Cao
School of Management, China University of Mining and Technology, Xuzhou, China and Jiangsu Energy Economics and Management Research Base, Xuzhou, China

Ming Cao
School of Public Administration, China University of Mining and Technology, Xuzhou, China, and

Shuang Li
School of Management, China University of Mining and Technology, Xuzhou, China

Received 25 November 2018
Revised 24 April 2019
1 October 2019
3 December 2019
20 January 2020
Accepted 5 March 2020

Abstract

Purpose – Presentation of the different industrial carbon linkages of India. The purpose of this paper is to understand the direct and indirect impact of these industrial linkages.

Design/methodology/approach – This study uses a hypothetical extraction method with its various extensions. Under this method, different carbon linkages of a block are removed from the economy, and the effects of carbon linkages are determined by the difference between the original and the post-removal values. Energy and non-energy carbon linkages are also estimated.

Findings – "Electricity, gas and water supply (EGW)" at 655.61 Mt and 648.74 Mt had the highest total and forward linkages. "manufacturing and recycling" at 231.48 Mt had the highest backward linkage. High carbon-intensive blocks of "EGW" plus "mining and quarrying" were net emitters, while others were net absorbers. "Fuel and chemicals" at 0.08 Mt had almost neutral status. Hard coal was the main source of direct and indirect emissions.

Practical implications – Net emitting and key net forward blocks should reduce direct emission intensities. India should use its huge geographical potential for industrial accessibility to cheaper alternative energy. This alongside with technology/process improvements catalyzed by policy tools can help in mitigation efforts. Next, key net-backward blocks such as construction through intermediate purchases significantly stimulate emissions from other blocks. Tailored mitigation policies are needed in this regard.

This study was financially supported by the National Social Science Foundation of China (grant no. 15BGL175), and the National Natural Science Foundation of China (grant no. 71573253).

International Journal of Climate Change Strategies and Management
Vol. 12 No. 3, 2020
pp. 323-347
Emerald Publishing Limited
1756-8692
DOI 10.1108/IJCCSM-11-2018-0075

Originality/value – By developing an understanding of India's industrial carbon links, this study can guide policymakers. In addition, the paper lays out the framework for estimating energy and non-energy-based industrial carbon links.

Keywords India, Energy, Carbon emissions, Carbon intensity, Carbon linkages, Hypothetical extraction model

Paper type Research paper

Nomenclature

Acronyms full titles

AHF = Agriculture, hunting, forestry and fishing;
MQ = Mining and quarrying;
FBT = Food, beverages and tobacco;
MR = Manufacturing and recycling;
FC = Fuel and chemicals;
ME = Machinery and equipment;
EGW = Electricity, gas and water supply;
CON = Construction;
TC = Transport and communication;
MS = Miscellaneous services;
HCOA = Hard coal;
BCOA = Bituminous coal;
COKE = Coke;
CRUDE = Crude oil;
DIESEL = Diesel;
GASOLINE = Gasoline;
JETFUEL = Jet fuel;
LFO = Light fuel oil;
HFO = Heavy fuel oil;
NAPHTA = Naphtha;
OTHPETRO = Other petroleum;
NATGAS = Natural gas;
OTHGAS = Other gas;
Non-ENERGY = Non-energy;
ENBL = Emissions from net backward linkage;
ENFL = Emissions from net forward linkage;
EIL = Emissions from internal linkage;
EML = Emissions from mixed linkage;
Mt = Million tons;
HEM = Hypothetical extraction method; and
MHEM = Modified hypothetical extraction method.

1. Introduction

India, with a population of more than 1.32 billion as of 2016, is the second most populous country in the world (The World Bank, 2018). By 2030, India will become the most populous country in the world, surpassing China (United Nations, 2017). It is among the top 10 economies in the world (IMF, 2018). From 2014 to 2040, India is expected to be the fastest growing economy in the world (IEA, 2016). In these years, while the top two coal-consuming nations, China and the USA, will see their consumption decline, India's coal consumption will rise by an average of 2.6 per cent per year, and by 2020 India will surpass the USA to become the world's second-largest coal-consumer (EIA, 2017). All of these indicators signal a growing demand for energy and a pressure on the Indian economy's natural resources. Between 2000 and 2015 India's energy demand almost doubled, the rapid industrialization, urbanization and production catalyzed by the "Make in India" initiative will drive this pattern to linger (Tortajada and Saklani, 2018). India is ranked third-largest emitter of CO_2 behind China and the USA; this holds true for India's output and consumption-based emissions (Fan *et al.*, 2016).

India is the first country in the world to establish a dedicated "ministry for new and renewable energy" (Sinha and Shahbaz, 2018). It has a "national action plan on climate change" with eight main missions including, namely, "national mission on strategic knowledge for climate change; national mission for sustaining the Himalayan ecosystem; national solar mission; national mission for sustainable agriculture; national water mission; national mission for enhanced energy efficiency; national mission for a green India and national mission on sustainable habitat" (Chandel *et al.*, 2016). India is also an active participant in several international climate and environmental agreements and negotiations (Ministry of Environment, Forest and Climate Change, 2019). Despite all these efforts, India ranks 177th out of a total of 180 countries in terms of the environmental performance index (Yale Center for Environmental Law and Policy, 2018).

From 2014 to 2040, India will be the world leader in industrial demand (The Outlook for Energy, 2016). Keeping in mind the role that industries play in climate change, a deep understanding of the inter and intra-sectoral carbon linkages of these industries could play a key role in alleviating this impact, helping to achieve India's "climate action plan" objectives and fulfilling its international agreements and obligations. Conventionally, the main focus of industrial carbon mitigation efforts is to reduce direct emissions, but this paper, by integrating the hypothetical extraction method (HEM) with the input-output analysis, studies the impact of different energy plus non-energy-related direct and indirect inter-sectoral carbon links. The presentation of these upstream, downstream and intra-sectoral carbon linkages from different energy sources will be helpful in targeted reduction of emissions of the entire carbon chain of the Indian economy.

2. Literature review

Generally, the literature focuses on estimating direct carbon emissions while the complex inter-sectoral carbon linkages are usually overlooked (Wang *et al.*, 2013). Sectoral linkages are the links between the sector and others through both direct and indirect inter-sectoral imports and exports (Miller and Lahr, 2001). Four main approaches for inter and intra-sectoral linkage calculations can be found in the literature. The first in the list is the classical multiplier, suggested by Chenery and Watanabe (1958), where the sum of columns or rows of the direct input coefficient matrix is measured for backward or forward links. Here, the backward link of the industry is defined as the upstream link with its intermediate sellers, while the downstream intermediate link with its intermediate buyers is referred to as the forward link (Lenzen, 2003; Miller and Blair, 2009). The remaining three approaches to inter-sectoral linkage analysis are all based on a HEM. Where the sector is hypothesized to be removed from the economy, the impact of the deleted sector is measured by the difference between pre and post-extraction values. These include original HEM (Strassert, 1968), Cella's HEM (Cella, 1984) and modified hypothetical extraction method (MHEM) (Duarte *et al.*, 2002). The original HEM was initially used by Strassert (1968) and later by Schultz (1977); Meller and Marfán (1981) to study the economic impact of the industry, whereby a sector is completely extracted from a hypothetical economy, i.e. all inter and intra-sectoral links of the sector are removed from the economy. Because of the complete extraction of a sector it is also referred to as a sector's "shutdown" linkage (Groenewold *et al.*, 1987).

Dietzenbacher and van der Linden (1997) pointed out that the original HEM could not provide us with separate measures for both forward and backward sectoral links. Cella (1984) criticized Schultz (1977) and Meller and Marfán (1981) in their original HEM approach, thinking that they had either under or over-estimated total links. Cella redefined total linkage, plus decomposed it into backward and forward sectoral linkages. In Cella (1984) HEM, all external links related to a sector or a group of sectors are extracted from the economy, whereas internal links are not removed from that economic system. Finally, the MHEM by which Cella's proposal was further broken down by Duarte *et al.* (2002) into mixed, internal, net forward and net back linkages.

Thus, industrial linkage measurement methods can be broadly categorized under two main headings, the conventional direct multiplier approach and the HEM and its various extensions. Because of its simplicity, the conventional multiplier has been extensively used to study inter-industrial environmental and carbon linkages (Chen *et al.*, 2017; Zhang, 2010; Tian *et al.*, 2012; Lenzen, 2003; Sun *et al.*, 2017). Conventional multiplier approach cannot calculate the relative size of the sector impact, the conventional multiplier, due to its tendency to ignore the size disparity between sectors, can give misleading accounts of the relative strength of the sectoral linkages (Clements, 1990). HEM overcomes this weakness; it informs us of the magnitude of the sector's impact on the carbon linkages of other sectors of the economy. HEM is a perfection of the conventional multiplier approach, stimulates the importance of the sector by removing its linkages from the economic system, then the sector impact on economic activities can be measured by the output loss caused by the elimination of the target sector, and it is extremely useful to use the HEM in a multi-sectoral model to identify key sectors for the economy (Guerra and Sancho, 2010; Wang *et al.*, 2013).

Both original and Cella HEM have been used in literature to study industrial-economic linkages (Song *et al.*, 2006; Cai and Leung, 2004). HEM has also been applied to various dimensions and aspects related to environmental problems these include:

- water problem (Duarte *et al.*, 2002; Blanco and Thaler, 2014; Deng *et al.*, 2018);
- regional (Ali, 2015; Zhao *et al.*, 2015; Wang *et al.*, 2013) and inter-regional (Zhao *et al.*, 2016) sectoral carbon linkages;
- energy linkages (Guerra and Sancho, 2010);
- household carbon linkages at country (Zhang *et al.*, 2017a; Perobelli *et al.*, 2015; Zhang *et al.*, 2017b) and city (Tian *et al.*, 2017; Liao *et al.*, 2017) levels; and
- air pollutants at regional (He *et al.*, 2017) and inter-regional levels (Wang *et al.*, 2017a).

Specifically speaking of carbon links literature based on the HEM, Wang *et al.* (2013) estimated the Chinese economy's fossil-fuel-related carbon emissions based on the MHEM. They suggested more penetration of less carbon-intensive energy into China's energy industry block. Zhao *et al.* (2016) used a multi-regional input-output model with a HEM to study China's industrial carbon linkages at regional level. In this study, China was divided into 8 regions and 10 industrial blocks. Bai *et al.* (2018) again analyzed the inter-sectoral fossil-fuel-based carbon flows of the Chinese economy using the MHEM.

In addition to China, other countries' industrial carbon links are also presented in the literature. Zhao *et al.* (2015) using Cella and MHEM estimated different dimensions of fossil-fuel-based direct and indirect carbon linkages of the South African economy. Ali (2015) compared different approaches by applying the Leontief model to backward linkages and the

Ghosh model to forward carbon links under the classic multiplier, the original HEM and the Cella HEM approaches. Sajid *et al.* (2019a) used the original and hybrid MHEM methods under the Leontief inverse and Ghosh supply models to calculate the: demand-pulled and supply-pushed sectoral CO_2 linkages of Turkey for 2009. Sajid *et al.* (2019b) used the MHEM method to estimate the CO_2 linkages of the transport sector of the top seven EU carbon discharging nations from 1995 to 2011. Sajid *et al.* (2019c) used the Cella and MHEM approaches to quantify the carbon linkages of the mining sector of the world's 10 largest economies.

Overall, there is little research on the complex industrial carbon linkages of the Indian economy under the HEM. The literature on Indian carbon emissions focuses mainly on:

- direct and indirect industrial emissions (Sun *et al.*, 2017; Mohan, 2018; Choudhary *et al.*, 2018);
- renewable energy (Sinha and Shahbaz, 2018; Mittal *et al.*, 2016; Anandarajah and Gambhir, 2014);
- regional and comparative emissions (Ramachandra *et al.*, 2015; Pappas *et al.*, 2018; Singh, 2011);
- energy (Morrow *et al.*, 2014; S.Parikh and K.Parikh, 2016; Ramachandra *et al.*, 2017);
- driving factors (Ahmad *et al.*, 2016; Alama *et al.*, 2016; Pal and Mitra, 2017);
- policy (Goodman, 2016; Stern and Jotzo, 2010; Aggarwal, 2017; Pradhan *et al.*, 2017);
- sources of power generation (Raghuvanshi *et al.*, 2006; Mishra *et al.*, 2015; Kumar *et al.*, 2017); and
- road transport (Dhar *et al.*, 2017; Paladugula *et al.*, 2018; Malik and Tiwari, 2017).

There are the following shortcomings with the existing industrial carbon linkage literature under HEM. First, to the best of the authors knowledge, almost all carbon linkage literature using HEM aggregates total emissions from the use of different types of fossil fuels, rather than reporting these emissions from the use of different fossil fuels separately. Second, there is no such study available that provides both energy and non-energy-related industrial carbon links for a particular economy. Finally, there is not much literature available on the complex inter-sectoral carbon linkages of the Indian economy, especially under the HEM method. This paper addresses these important research gaps and develops a methodology for determining different fossil-fuel-based and non-energy-based direct and indirect industrial carbon links. A comprehensive analysis of the various industrial carbon linkages and their major energy and non-energy sources can help India's Government with targeted mitigation efforts. Not only can it provide information on key carbon industrial blocks but also inform us about the main energy (fossil-fuel) and non-energy sources of these direct and indirect sectoral carbon emissions. In addition, India is one of the largest industrial powers with a high gross domestic product (GDP) and population growth rate. It is of great importance to understand the complex inter-industrial carbon connections of the Indian economy. A comprehensive analysis of these links will help with the ongoing mitigation efforts of the Government of India and related agencies.

3. Methodology

3.1 Leontief model

The basic Leontief model (Leontief, 1936) can be presented as:

$$X = AX + Y \tag{1}$$

By segregation of X we have:

$$X = (I - A)^{-1} Y \tag{2}$$

Where X is the total output, I represents a fitting identity matrix; A is direct requirement matrix where $a_{ij=\frac{x_{ij}}{x_j}}$ represents per unit direct demand of i from j, $(I - A)^{-1}$ denoted as L is Leontief inverse matrix.

3.2 Total direct intensity and its decomposition into energy and non-energy emission intensities

If we present total emissions of an economy by E and total output by X. Then, a ratio of E_i to X_i will yield total direct carbon intensity of sector i (Liu *et al.*, 2010).

$$e_i = \frac{E_i}{X_i} \tag{3}$$

Where e_i represents the total direct emission intensity of sector i.

Here, the authors develop the methodology to decompose total emissions intensity into energy and non-energy-related emission intensities.

$$e_i = e_i^p + e_i^n = \frac{E_i}{X_i} = \frac{E_i^p}{X_i} + \frac{E_i^n}{X_i} \tag{4}$$

Where e_i represents total direct emission intensity of sector i, e_i^p represents sectoral energy-related emission intensities while e_i^n represent non-energy-related sectoral emission intensities. Here E_i^p denotes total energy-related carbon emissions and E_i^n represent total non-energy-related emission of Indian economy.

e_i^p can be further decomposed into different fossil fuel types.

$$e_i^p = \frac{\sum_{l=1}^{m} E_i^l}{X_i} \tag{5}$$

Where E_i^l represents direct carbon emissions generated by the use of fuel type l (l = 1, 2, 3, . . ., m) in sector i.

3.3 Calculation of direct emissions

By multiplying diagonalized environmental emission intensity vector e, with total output vector X, total sectoral carbon emissions can be obtained:

$$E = eX = e(I - A)^{-1} Y \tag{6}$$

For the estimation of different types of energy and non-energy-related emissions, authors simply replaced total emission intensity with emissions intensities of energy and non-energy-related emissions.

$$E^p = e_i^p X = e_i^p (I - A)^{-1} Y \tag{7}$$

$$E^n = e_i^n X = e_i^n (I - A)^{-1} Y \tag{8}$$

Where E^p and E^n represent carbon emissions from energy and non-energy-related sources.

3.4 Hypothetical extraction method for carbon emissions linkage analysis

Strassert (1968) is considered to be the pioneer of HEM, later on, Schultz (1977) studied sectoral economic linkages under HEM, some modifications were introduced by (Duarte *et al.*, 2002; Clements, 1990; Cella, 1984).

For easiness, Indian economy can be presented by two blocks, namely, extracted block τ_s and τ_{-s} representing the rest of Indian economy. Subsequent Indian economy τ is defined as:

$$\tau = \begin{bmatrix} \tau_{s,s} & \tau_{s-,s} \\ \tau_{-s,s} & \tau_{-s,-s} \end{bmatrix} \tag{9}$$

Total carbon emissions E can be presented as:

$$E = \begin{bmatrix} E_s \\ E_{-s} \end{bmatrix} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \begin{bmatrix} X_s \\ X_{-s} \end{bmatrix} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \left(\begin{bmatrix} A_{s,s} & A_{s,-s} \\ A_{-s,s} & A_{-s,-s} \end{bmatrix} \begin{bmatrix} X_s \\ X_{-s} \end{bmatrix} + \begin{bmatrix} Y_s \\ Y_{-s} \end{bmatrix} \right)$$
$$= \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \begin{bmatrix} \vartheta_{s,s} & \vartheta_{s,-s} \\ \vartheta_{-s,s} & \vartheta_{-s,-s} \end{bmatrix} \begin{bmatrix} Y_s \\ Y_{-s} \end{bmatrix} \tag{10}$$

Where total emissions are represented by $E = \begin{bmatrix} E_s \\ E_{-S} \end{bmatrix}$, direct carbon intensity $= \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix}$, total output vector $= \begin{bmatrix} X_s \\ X_{-s} \end{bmatrix}$, vector of final demand $= \begin{bmatrix} Y_s \\ Y_{-s} \end{bmatrix}$, $A = \begin{bmatrix} A_{s,s} & A_{s,-s} \\ A_{-s,s} & A_{-s,-s} \end{bmatrix}$ is direct requirement matrix and $(\mathrm{I} - \mathrm{A})^{-1} = \begin{bmatrix} \vartheta_{s,s} & \vartheta_{s,-s} \\ \vartheta_{-s,s} & \vartheta_{-s,-s} \end{bmatrix}$ is the Leontief inverse matrix.

One of the most popular approaches to the calculation of inter-sectoral linkages is the Cella (1984) proposal. In contrast to the extraction of all linkages of the sector under the original HEM, Cella suggested that only external links, i.e. inter-sectoral imports and exports of the sector, should be removed. The internal links of the sector should be retained. Corresponding scenario under Cella proposal can be presented as:

$$\overline{E} = \begin{bmatrix} \overline{E}_s \\ \overline{E}_{-s} \end{bmatrix} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \begin{bmatrix} X_s \\ X_{-s} \end{bmatrix} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \left(\begin{bmatrix} A_{s,s} & 0 \\ 0 & A_{-s,-s} \end{bmatrix} \begin{bmatrix} X_s \\ X_{-s} \end{bmatrix} + \begin{bmatrix} Y_s \\ Y_{-s} \end{bmatrix} \right)$$
$$= \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \begin{bmatrix} (I - A_{s,s})^{-1} & 0 \\ 0 & (I - A_{-s,-s})^{-1} \end{bmatrix} \begin{bmatrix} Y_s \\ Y_{-s} \end{bmatrix} \tag{11}$$

Extracted block impact on emissions, which is mainly due to the difference in production is presented as:

$$\Delta E = E - \overline{E} = \begin{bmatrix} E_s - \overline{E}_s \\ E_{-s} - \overline{E}_{-s} \end{bmatrix} = \begin{bmatrix} e_s & 0 \\ 0 & e_{-s} \end{bmatrix} \begin{bmatrix} \vartheta_{s,s} - (I - A_{s,s})^{-1} & \vartheta_{s,-s} \\ \vartheta_{-s,s} & \vartheta_{-s,-s} - (I - A_{-s,-s})^{-1} \end{bmatrix} \begin{bmatrix} Y_s \\ Y_{-s} \end{bmatrix} =$$
$$\begin{bmatrix} \omega_{s,s} & \omega_{s,-s} \\ \omega_{-s,s} & \omega_{-s,-s} \end{bmatrix} \begin{bmatrix} Y_s \\ Y_{-s} \end{bmatrix} \tag{12}$$

The absolute valued total linkage can be presented as:

$$CTL = \hat{u}\begin{bmatrix} E_s - \overline{E}_s \\ E_{-s} - \overline{E}_{-s} \end{bmatrix}\begin{bmatrix} Y_s \\ Y_{-s} \end{bmatrix} \tag{13}$$

Where CTL represents Cella's total linkage, $\hat{u}$ is a summation vector. Corresponding Cella backward and forward linkages can be presented as:

$$CBL = \hat{u}e_s\left[\vartheta_{s,s} - \left(I - A_{s,s}\right)^{-1}\right]Y_s + \hat{u}e_{-s}[\vartheta_{-s,s}]Y_s \tag{14}$$

Where CBL represents Cella's decomposition into the backward linkage.

$$CFL = \hat{u}e_s[\vartheta_{s,-s}]Y_{-s} + \hat{u}e_{-s}\left[\vartheta_{-s,-s} - \left(I - A_{-s,-s}\right)^{-1}\right]Y_{-s} \tag{15}$$

Where CFL represents Cella's decomposition into the forward linkage.

Duarte *et al.* (2002) developed the relative index for sectoral linkage analysis.

$$CTL_i^* = \frac{CTL_i}{\frac{1}{k}\sum_{i=1}^{k} CTL_i} \tag{16}$$

$$CBL_i^* = \frac{CBL_i}{\frac{1}{k}\sum_{i=1}^{k} CBL_i} \tag{17}$$

$$CFL_i^* = \frac{CFL_i}{\frac{1}{k}\sum_{i=1}^{k} CFL_i} \tag{18}$$

Where CTL_i^*, CBL_i^* and CFL_i^* represent Cella total, forward and backward carbon linkage relative indices of block i, here k = (1, 2, 3, …, k) represents the total number of blocks. A value of more than one indicates that block i carbon linkage is above average.

3.5 Modified hypothetical extraction model

Cella's proposal was further decomposed by Duarte *et al.* (2002) into a net backward, net forward, mixed and internal links. Net back emissions are defined as the emissions associated with the sector's intermediate purchases. Net forwards with intermediate sales. Internal emissions are linked to intra-sectoral demand. Finally, mixed emissions are initially sold to other sectors and then repurchased from them. These can be defined as below.

Emissions from internal linkage:

$$EIL = \hat{u}e_s\left(I - A_{s,s}\right)^{-1}Y_s \tag{19}$$

Emissions from mixed linkage:

$$EML = \hat{u}e_s\left[\vartheta_{s,s} - \left(I - A_{s,s}\right)^{-1}\right]Y_s \tag{20}$$

Emissions from net backward linkage (ENBL):

$$ENBL = \hat{u}e_{-s}[\vartheta_{-s,s}]Y_s \tag{21}$$

Emissions from net forward linkage (ENFL):

$$ENFL = \hat{u}e_s[\vartheta_{s,-s}]Y_{-s} \tag{22}$$

Zhao *et al.* (2015) explained the relationship of Cella backward and forward carbon linkages of target block s and net transferred emissions (NTEs) from extracted block through the following equations (23)-(25):

$$CBL_s = EML_s + ENBL_s \tag{23}$$

$$CFL_s = ENFL_s + EML_{-s} \tag{24}$$

$$NTE = ENFL - ENBL \tag{25}$$

Here, a positive balance of NTE will show that the block is a net emitter, a negative balance will indicate that the block is net absorber, while 0 will indicate neutral emission status of the specific block.

3.6 Decomposition of emissions from net backward linkage and emissions from net forward linkage

ENBL and *ENFL* can be further decomposed. Suppose there are a total k number of blocks in the economy, block r is one of the blocks other than target block s. Then, the total net backward carbon emission transfer form s to $-s$ can be further divided as:

$$ENBL_s = \sum_{r=0}^{k-1} ENBL_{r\to s} = \sum_{r=0}^{k-1} e_r\boldsymbol{\omega}_{r,s}Y_s = \sum_{r=0}^{k-1} e_r\vartheta_{r,s}Y_s \tag{26}$$

Where $ENBL_s$ represent total net backward emissions from block r to s of a country.

Correspondingly net forward emissions from s to r will be:

$$ENFL_s = \sum_{r=0}^{k-1} ENFL_{s\to r} = \sum_{r=0}^{k-1} e_s\boldsymbol{\omega}_{s,r}Y_r = \sum_{r=0}^{k-1} e_s\vartheta_{s,r}Y_r \tag{27}$$

Where $ENFL_s$ represent total net forward emissions from block s to block r of a country.

3.7 Calculation of net backward and net forward emissions from the use of different types of fossil fuels and non-energy sources

In this section, the authors develop a methodology for calculating net backward (purchase) and net forward emissions from the use of different fossil and non-energy uses.

By replacing the total direct-intensity vector with the energy-intensity (fossil fuels) and non-energy-use vectors in equation (21), backward emissions caused by these different uses can be obtained.

$$ENBL^{p} = \hat{u}e^{p}_{-s}[\vartheta_{-s,s}]Y_{s} \quad (28)$$

$$ENBL^{n} = \hat{u}e^{n}_{-s}[\vartheta_{-s,s}]Y_{s} \quad (29)$$

Where $ENBL^{p}$ and $ENBL^{n}$ represent net backward emissions caused by the energy and non-energy use of a sector's carbon purchases from upstream sectors.

Similarly, by replacing the total direct intensity with emissions intensity from energy (fossil fuels) and non-energy use in equation (22), the net forward emissions caused by these different uses can be obtained.

$$ENFL^{p} = \hat{u}e^{p}_{s}[\vartheta_{s,-s}]Y_{-s} \quad (30)$$

$$ENFL^{n} = \hat{u}e^{n}_{s}[\vartheta_{s,-s}]Y_{-s} \quad (31)$$

Where $ENFL^{p}$ and $ENFL^{n}$ represent industrial emissions from the use of energy and non-energy sources to fulfill its inter-sectoral sales demand.

4. Data sources and classification

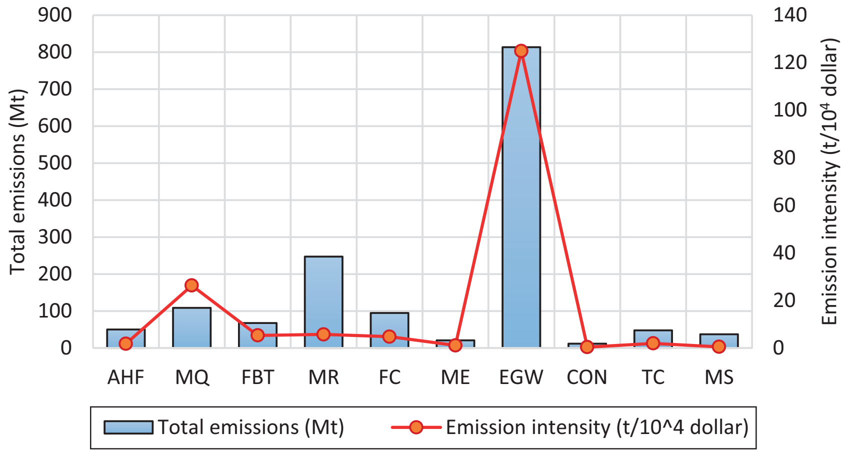
The world input output database (WIOD) is used for this study. The WIOD database is considered to be a reliable data source for environmental research in general (Fan *et al.*, 2017; Wang *et al.*, 2017b; Kucukvar *et al.*, 2015) and for industrial carbon link analysis in particular (Ali, 2015; Sajid *et al.*, 2019b). It has been released in 2013 and 2016, but the 2016 release does not include environmental accounts. On the other hand, the 2013 release includes the 1995-2011 input-output tables and the socio-economic accounts (Timmer *et al.*, 2015) plus the 1995-2009 environmental accounts (Genty *et al.*, 2012). The year 2009 is selected based on the availability of the most recent environmental accounts. Under the release of 2013, the Indian economy is divided into 35 sectors. The "private households with employees" sector lacking environmental accounts and the "public administrator and defense; compulsory social security" sector lacking intermediate sector sales and purchases are not included in this study. The authors have aggregated the Indian economy into 10 major blocks. Appendix section contains the details.

5. Results

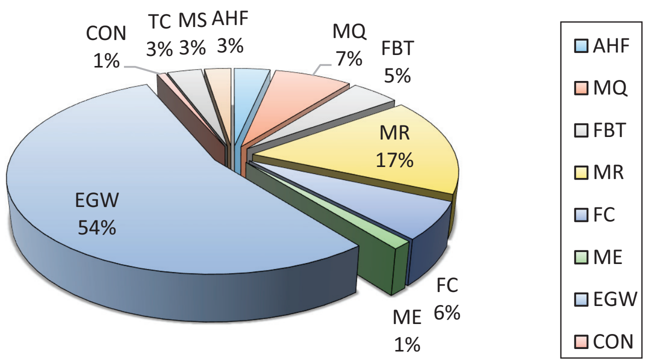
5.1 Total carbon emissions and intensity

Using equations (2) and (3) total carbon emissions and intensity of the Indian economy can be obtained, Figure 1 contains details. The Indian economy's total estimated carbon emissions in 2009 were 1,500.96 Mt. electricity, gas and water supply (EGW) had an enormous share of 54 per cent of India's total emissions. High demand for EGW as the primary energy source and carbon-intensive production are key determinants. The manufacturing and recycling (MR) block is the main source of employment, exports and income generation for the economy, with 17 per cent of total emissions was at second place. It was followed by mining and quarrying (MQ) 7 per cent, which is the main source of non-agricultural raw material, fuel and chemicals (FC) with 6 per cent of total emissions was at fourth. Overall, the main emissions were from blocks consisting of the primary and secondary industries, while blocks consisting of the territorial industries, including transport and communication (TC) and miscellaneous services (MS), contributed only 6 per cent of the total emissions for 2009.

The highest carbon-intensive block was EGW with 124.93 t/10^4 \$. This alarmingly high intensity is mainly because of the fact that almost 64.8 per cent of India's electricity comes from thermal sources. Out of this 64.8 per cent, coal accounts for 57.3 per cent, gas for 7.2 per



(a)



(b)

Figure 1.
(a) Total carbon emissions and intensities and (b) block-wise ratio of total carbon emissions

cent and oil only accounts for 0.2 per cent (Ministry of Power, 2018). Second on the list was MQ 26.33 t/10^4 \$, possible causes could be obsolete technologies and methods, plus high dependence on fossil fuels (Sajid *et al.*, 2019c). It was followed by MR 5.74 t/10^4 \$, food, beverages and tobacco (FBT) 5.33 t/10^4 \$ and FC 4.79 t/10^4 \$, respectively. The construction (CON) with 0.40 t/10^4 \$was the least carbon-intensive block of Indian economy.

5.2 Absolute and relative indices of carbon linkages
The authors used equations (8), (9) and (10) to estimate the absolute indices for Cella total, forward and backward linkages; the details are shown in Figure 2(a). The EGW block, which is the backbone of every economy and a key source of energy for other blocks of the economy, had the highest total link of 655.61 Mt. "Ministry for new and renewable energy" should find alternative ways to reduce high ratio of coal dependence by the electricity sector. It was followed by MR (483.10 Mt), CON (262.57 Mt) and FC (224.13 Mt), respectively. EGW also had the highest absolute Cella forward linkage value of 648.74 Mt while a very low

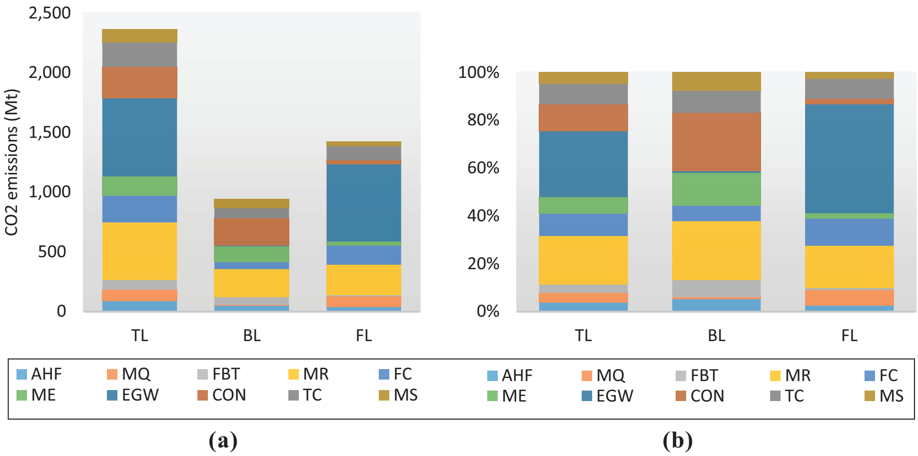


Figure 2.
(a) Absolute and (b) relative indices of Cella total, backward and forward carbon linkages

backward linkage value of 6.87 Mt. MR besides having highest Cella backward carbon linkage of 231.48 Mt, had a very strong forward linkage value of 251.61 Mt.

A better sense and understanding of total, backward and forward carbon linkages can be drawn from relative indices. A value of greater than 1 uses that the block has more than an average impact. Equations (11)-(13) were used to obtain these indices. The details are shown in Figure 2(b). EGW had the highest total relative value of 2.77. Other blocks who had a relative total linkage value of more than 1 were MR (2.04) and CON (1.11), respectively. MR with 2.46 had the highest relative backward carbon linkage. Other blocks with a relative backward linkage value of more than 1 were CON (2.44) and machinery and equipment (ME) (1.11), respectively. EGW with 4.56 had the highest relative forward linkage value. It was followed by MR (1.77) and FC (1.14), respectively.

5.3 Decomposition of industrial carbon linkages under modified hypothetical extraction model

Equations (15)-(18) and (21) were used to decompose the industrial carbon linkages of India. Figure 3 shows the graphical presentation of the decomposed carbon linkages of the Indian

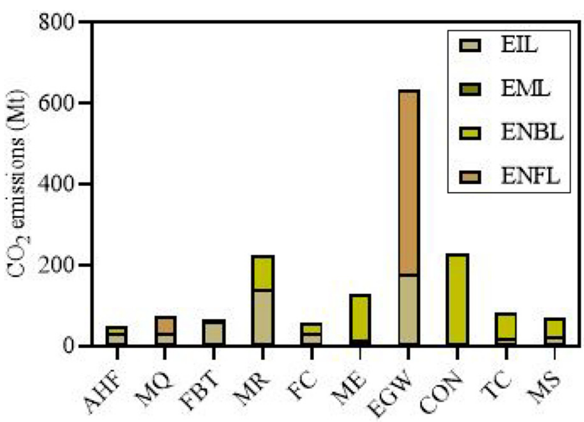


Figure 3.
Decomposed emissions from EIL, EML, ENBL and ENFL

economy. EGW at 178.02 Mt had the largest internal link (EIL) emissions. It was followed by MR (143.56 Mt), FBT (61.07 Mt) and agriculture, hunting, forestry and fishing (AHF) (34.69 Mt), respectively. The lowest amount of internal carbon emissions at 10.36 Mt was from CON. The MR with 4.47 Mt had the highest carbon emissions from mixed linkages. It was followed by EGW (2.41 Mt), FC (1.55 Mt) and TC (1.10 Mt), respectively. ENBL are those resulting from net imports (purchases) of a specific block from other industrial blocks. Blocks that significantly imported emissions from other blocks were CON (229.43 Mt), MR (227.01 Mt), TC (85.16 Mt) and MS (71.90 Mt), respectively. ENFL are those arising from net exports (sales) of a specific block to other blocks of the economy. The largest net exporting (emitting) block was EGW (633.09 Mt), followed by MR (99.31 Mt), MQ (74.58 Mt) and FC (59.96 Mt), respectively.

The authors consider equation (20) to measure the net transfer of emissions of a specific block to the Indian economy. Figure 4 is the graphic illustration. NTEs can explain whether a block is a net emitter or a net absorber of emissions. High carbon-intensive EGW (628.63 Mt) and MQ (67.83 Mt) blocks were the main emitters of carbon emissions. These two blocks are the key to carbon mitigation efforts as they absorb less and emit more. The FC with 0.08 Mt had almost neutral status. Compared to EGW and MQ, the remaining seven less carbon-intensive blocks, including AHF (−33.79 Mt), FBT (−60.15 Mt), MR (−127.70 Mt), FC (−125.28 Mt), TC (−60.06 Mt) and MS (−61.57 Mt), were net carbon absorbers. The least carbon-intensive block of all CON with −227.98 Mt was the highest absorber of emissions from other blocks of the Indian economy.

5.4 Further decomposition of emissions from net backward linkage and emissions from net forward linkage

Using equations (21) and (22), the authors further decomposed the emissions from the net back and the net forward inter-sectoral carbon linkages. This further decomposition will help us to understand that within the overall mix of the net backward link from which industry the target block absorbs what quantity of carbon emissions? Likewise, the further decomposition of net forward emissions would reflect the amount of carbon emissions exported to different sectors of the Indian economy. Figure 5 displays the graphical analysis of the further decomposition of ENBL and ENFL.

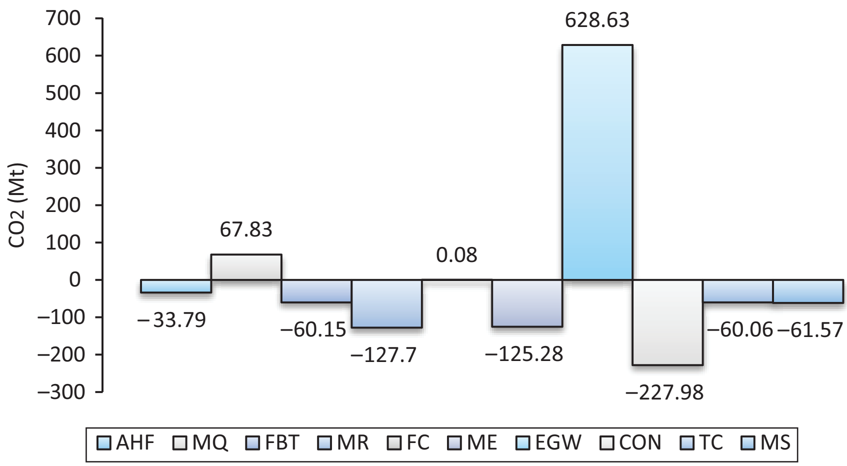


Figure 4.
Net transferred emissions of Indian economy

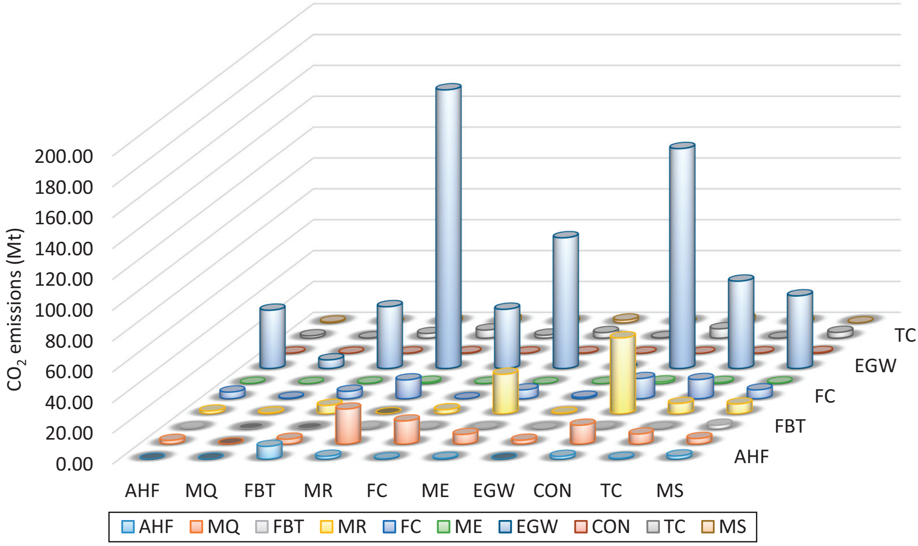


Figure 5.
Decomposed ENBL and ENFL

It is cleared that construction with a total of 229.43 Mt was the largest purchaser of emissions from other industries. Where the highest emission quantity of 142.49 Mt was obtained from EGW and the lowest emission quantity of 0.79 Mt from the FBT. On the other hand, the highest total ENFL was from the EGW block (633.09 Mt) with the largest quantity of emissions exported to MR (180.56 Mt). While the lowest quantity of emissions was exported to MQ (5.57 Mt).

5.5 Direct, net backward and net forward emissions from different fossil fuel types and non-energy sources

The authors used equations (7), (8) and (28)-(31) for calculating the direct, backward and forward emissions caused by the use of different energy and non-energy-related sources. Almost, 94 per cent of direct and 95 per cent of external (backward and forward) industrial carbon emissions were energy-related, which means that the Indian Government should pay close attention to improving the energy efficiency and energy structure of Indian industries. The use of hard coal (HCOAL) alone was responsible for approximately 68 per cent of the total direct and 75 per cent purchase and sale emissions of the Indian economy. Approximately 89 per cent of the direct and forward emissions of the EGW block originated from the use of hard coal. CON, India's largest carbon importer, had almost 74 per cent of its backward carbon impact from the use of HCOAL by its upstream exporters. Figure 6 represents the graphical illustration. After HCOAL, light fuel oil (LFO) with 7 per cent was the second-largest source of direct industrial emissions. While natural gas with 6 per cent was the second greatest source of external (net backward and forward) industrial emissions of the Indian economy.

6. Conclusion, discussion and policy implications

6.1 Conclusion

The various aspects of the direct and indirect impacts of the industrial carbon linkages of the Indian economy have been discussed in detail in this study. The study began with the

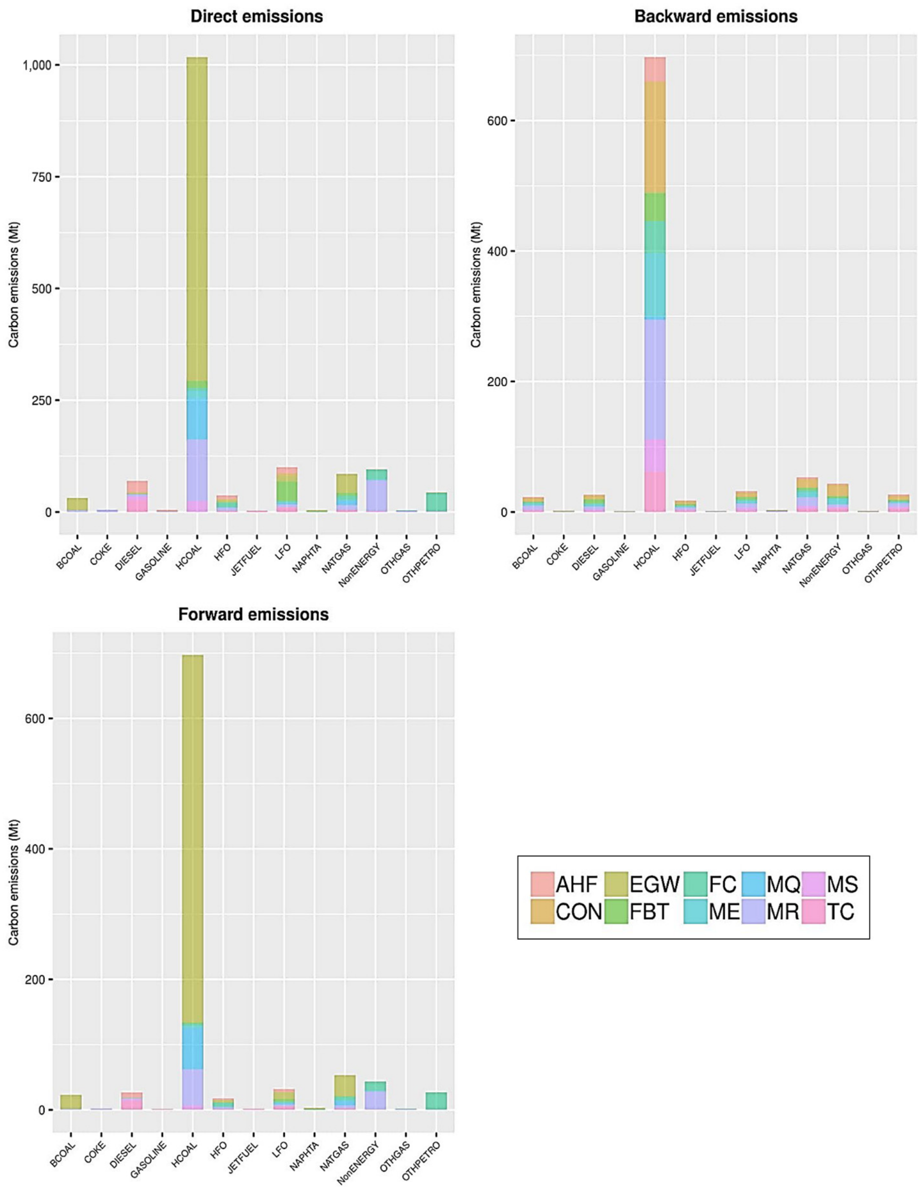


Figure 6.
Direct, net backward and net forward emissions from different fossil fuel types and non-energy sources

presentation of the total industrial emission and emission intensity followed by the use of the hypothetical extraction model under the Cella (1984) proposal, the MHEM (Duarte *et al.*, 2002), the further decomposition of net back and forward linkages and the estimation of direct and external emissions from the use of different energy types and non-energy sources. Generally, EGW had the greatest direct and indirect carbon impact on the Indian economy. Except for the backward linkages where the MR and the CON had the greatest impact.

Energy-related emissions were the main source of direct and indirect emissions from India. HCOAL was the main fuel for energy-related emissions.

6.2 Discussion

- EGW with 813.52 Mt, which accounted for 54 per cent of total direct emissions, was the largest emitter in 2009. It with 124.93 t/10^4 dollar was also the most carbon-intensive industrial block of the Indian economy. Not only this but also the EGW had the highest total, Cella backward, Cella forward, internal and net forward linkages impact on carbon emissions of the Indian economy. These results are fairly in line with the findings of Sun *et al.* (2017) indicating EGW consistently remained the largest direct emitter of the Indian economy from 1995 to 2009. Furthermore, their results show secondary industries to be the biggest source of direct emissions for the Indian economy[1]. This study also indicated that the primary and secondary industries contributed approximately 94 per cent of India's total direct emissions. Zhao *et al.* (2015) also indicated EGW having the largest direct, total, Cella forward, net forward and internal carbon impacts on energy-related industrial carbon emissions of the South African economy. Several other research on industrial carbon linkages has also shown that EGW has a substantial carbon effect on the respective economies under investigation (Ali, 2015; Zhao *et al.*, 2016). Our findings, backed by other studies, indicate that EGW is without question the key to reducing the carbon emissions of the Indian economy. Without improving EGW's hugely carbon-intensive production and supply, it will be extremely difficult for India to achieve its "20-25 per cent reduction in emission intensity of GDP by 2020 compared to 2005 levels" (Ministry of Environment, Forest and Climate Change, 2015).
- The MR block is the leading manufacturer of finished and semi-finished products. It is India's second largest direct carbon emitter with 17 per cent of total emissions. At the same time, it is the only industrial block in the Indian economy with more than average backward and forward carbon ties. This indicates that MR has induced a large amount of emissions through its intermediate demand for raw materials from the upstream industries. In addition, the sector also had more than average carbon demand from its downstream carbon importers. It means that this block has to improve both its carbon demand and supply structures. To reduce its backward linkage impact, it should reduce the amount of dirty (high carbon-intensive) imports, and for reduction of forward linkage impacts, it should improve its direct energy/carbon efficiency.
- CON, with roughly 1 per cent, contributed the least to the overall direct carbon emissions of the Indian economy. It was also the least carbon-intensive block but had the highest net carbon purchases from other sectors of the economy. This suggests that CON through its inter-sectoral imports has induced a large amount of carbon emissions from other industries. The Indian Government must take this into account in its strategies and efforts to reduce carbon emissions. Recent research has also shed light on this enormous indirect impact of the CON on national carbon emissions (Bai *et al.*, 2018).
- Mixed carbon emissions from India due to a very small size are not very significant from a policy point of view. While different industrial blocks had quite considerable emissions from internal carbon linkages. EGW at 178.02 Mt had the highest internal link (EIL) emissions. It was followed by MR (143.56 Mt) and FBT (61.07 Mt), respectively. In addition to improving external trade patterns, these key carbon

blocks also need to pay attention to their internal demand structures. Net total is the difference between emissions from ENFL (net forward linkage) and ENBL (net backward linkage), a positive difference indicates that the block is net emitter (exporter) of emissions while a negative balance means the contrary. The main net emitters of the Indian economy were EGW (628.63 Mt) and MQ (67.83 Mt), respectively, while the top three net absorbing blocks were CON (−227.98 Mt), MR (−127.70 Mt) and MS (−61.57 Mt), respectively.

- Further decomposition of ENFL and ENBL shows us, within the overall mix of these forward and back linkages, how much emissions from a particular block have been transferred to or absorbed from each remaining block. EGW having the highest ENFL value of 628.63 Mt, emitted (exported) largest portion of its emissions to MR (180.56 Mt). While CON, having the highest ENBL value of 229.43 Mt, absorbed (imported) largest portion of its emissions from EGW (142.49 Mt). MR having the second-highest backward linkage impact also imported a considerable amount of 180.56 Mt of emissions from the EGW. While it is the highest amount of carbon sales were to the CON (49.34 Mt) sector. This shows a significant dependence of high-carbon importers (CON and MR) on high-carbon exporters such as EGW. Thus, without taking into account the indirect impact of key downstream carbon buyers, i.e. without reducing the carbon demand of these key carbon importers, it will be difficult for key carbon producers to reduce their emissions.
- Approximately 95 per cent of Indian economic emissions were energy-related. Hard coal was the main source of direct and indirect carbon emissions of the Indian economy. Although the share of non-energy-related emissions was approximately 5-6 per cent, still these emissions should not be neglected in the governmental carbon reduction policies.

6.3 Policy implications

A comprehensive empiric analysis of the complex inter-sectoral carbon linkages of the Indian economy has allowed us to come up with possible policy implications for industrial carbon mitigation. India is the world's third largest carbon emitter with more carbon-intensive industries than major EU counterparts and China (based on WIOD environmental accounts). This is mainly because of high fossil fuel dependence (91.78 per cent) of Indian economy for primary energy, including 29.34 per cent from crude oil, 6.18 per cent from natural gas and 56.26 per cent from coal, respectively (Bp, 2018). To reduce carbon intensity, this huge dependence on fossil fuels as primary energy have to be reduced for that alternative energy sources should be considered. Based on the numerical findings, the authors propose the following policy implications for mitigation of direct and indirect industrial carbon emissions:

HCOAL, LFO and natural gas were the top three fossil fuel (energy-related) sources of carbon emissions. These three roughly accounted for 80 per cent of the Indian economy's direct and 84 per cent external (net backward and net forward) emissions. It is, therefore, very clear that the Government of India needs to improve the energy efficiency of these fuels in different industries. Many initiatives from upgrading existing technologies to replacing outdated energy-intensive ME can be put in place to improve efficiency. In addition, training of staff and managers on various energy-saving options is also required.

Non-energy sources account for approximately 6 per cent of the total and 5 per cent of the external emissions of the Indian economy. Indian Government should also consider reducing emissions from non-energy sources, options, like improving production processes and substituting gasses/products (used in non-combustible industrial activities causing carbon releases), can help in the reduction of both direct and indirect non-energy-related industrial carbon emissions.

The use of coal specifically "hard coal" was the main culprit for most of the direct and indirect carbon emissions of the Indian economy. The top carbon emitter and exporter of carbon emissions "EGW" had approximately 89 per cent of direct and forward emissions from the use of hard coal. That considering the projected rapid increase in India's coal consumption in the future, would undoubtedly undermine any reduction efforts on the part of the Indian Government. It is highly recommended that the Indian Government review its policies on the use of coal and get rid of its coal-based energy consumption as soon as possible. India should realize its huge potential for renewable energy, including small hydropower projects (current capacity 2,429.67 MW, potential 15,000 MW), solar energy (clear sky 260-300 days), wind energy (current capacity 10,242.5 MW, potential 45,195 MW), bio power (current capacity 703.3 MW, potential 16,881 MW), bagasse co-generation (current capacity 1,048.73 MW, potential 5,000 MW), energy recovery from waste (current capacity 92.97 MW, potential 2,700 MW), etc (Global Energy Network Institute, 2006). It will also reduce India's high dependence on expensive and less clean fossil fuel imports.

EGW and MQ were the main net emitters of the Indian economy's carbon emissions, which means that they import relatively less carbon-intensive goods and services but, in return, export relatively more carbon-intensive products, resulting in net carbon emissions. The Government of India should pay close attention to reducing the high carbon intensity of the sectors, particularly these two key carbon industrial blocks. In addition to the promotion of more renewable energy, there are several other direct and indirect options available to the Government of India. For example, carbon taxes could be introduced on the basis of net carbon transfers between sectors of the Indian economy. Carbon tax breaks and subsidies should be granted to sectors on the basis of their investments in carbon offset projects such as carbon sequestration (forestry), which will improve overall environmental quality and public health (Jindal *et al.*, 2007).

The Indian Government should also consider introducing voluntary carbon markets in the near future. In addition to focusing on high direct emitters, Indian policymakers in the future market should also take into account the main downstream stimulators of industrial carbon emissions. For example, most of EGW's carbon emissions are stimulated by the procurement of carbon by MR, CON and ME, etc. Studies have found that more cost-effective carbon mitigation potential is achieved by integrating the stimulating effects of carbon imports of key downstream buyers into carbon trading and credit allocation schemes (Bai *et al.*, 2018). With further economic development, the government can amend the legislation to make carbon trading compulsory.

Although net emitters are primarily responsible for the Indian environment, significant net absorbing blocks can also play a role in carbon mitigation. Net import blocks stimulate emissions of other blocks through their intermediate purchases; they can encourage or in some rare cases, force exporters to reduce their high emission intensities.

Note

1. Sun *et al.* (2017) included the "mining and quarrying" in the category of secondary industry. Normally, this sector is considered as a primary industry.

References

Aggarwal, P. (2017), "2 C target, India's climate action plan and urban transport sector", *Travel Behaviour and Society*, Vol. 6, pp. 110-116.

Ahmad, A., Zhao, Y., Shahbaz, M., Bano, S., Zhang, Z., Wang, S. and Liu, Y. (2016), "Carbon emissions, energy consumption and economic growth: an aggregate and disaggregate analysis of the Indian economy", *Energy Policy*, Vol. 96, pp. 131-143.

Alama, M.M., Muradb, M.W., Noman, A.H.M. and Ozturk, I. (2016), "Relationships among carbon emissions, economic growth, energy consumption and population growth: testing environmental Kuznets curve hypothesis for Brazil, China, India and Indonesia", *Ecological Indicators*, Vol. 70, pp. 466-479.

Ali, Y. (2015), "Measuring CO_2 emission linkages with the hypothetical extraction method (HEM)", *Ecological Indicators*, Vol. 54, pp. 171-183.

Anandarajah, G. and Gambhir, A. (2014), "India's CO_2 emission pathways to 2050: what role can renewables play?", *Applied Energy*, Vol. 131, pp. 79-86.

Bai, H., Feng, X., Hou, H., He, G., Dong, Y. and Xu, H. (2018), "Mapping inter-industrial CO_2 flows within China", *Renewable and Sustainable Energy Reviews*, Vol. 93, pp. 400-408.

Blanco, C.D.P. and Thaler, T. (2014), "An input-output assessment of water productivity in the Castile and león region (Spain)", *Water*, Vol. 6, pp. 929-944.

Bp (2018), "BP statistical review of world energy", British Petroleum, London, available at: www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

Cai, J. and Leung, P. (2004), "Linkage measures: a revisit and a suggested alternative", *Economic System Research*, Vol. 16, pp. 65-85.

Cella, G. (1984), "The input-output measurement of interindustry linkages", *Oxford Bulletin of Economics and Statistics*, Vol. 46 No. 1, pp. 73-84.

Chandel, S., Shrivastva, R., Sharma, V. and Ramasamy, P. (2016), "Overview of the initiatives in renewable energy sector under the national action plan on climate change in India", *Renewable and Sustainable Energy Reviews*, Vol. 54, pp. 866-873.

Chen, G., Hadjikakou, M. and Wiedmann, T. (2017), "Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input-output analysis", *Journal of Cleaner Production*, Vol. 163, pp. 224-240.

Chenery, H. and Watanabe, T. (1958), "International comparisons of the structure of production", *Econometrica*, Vol. 4, pp. 487-521.

Choudhary, P., Srivastava, R.K. and De, S. (2018), "Integrating greenhouse gases (GHG) assessment for low carbon economy path: Live case study of Indian national oil company", *Journal of Cleaner Production*, Vol. 198, pp. 351-363.

Clements, B. (1990), "On the decomposition and normalization of interindustry linkages", *Economics Letters*, Vol. 33 No. 4, pp. 337-340.

Deng, G., Wang, L. and Xu, X. (2018), "Linkage effect of virtual water trade in china's industrial products—based on generalized hypothetical extraction method", *Ecological Indicators*, Vol. 93, pp. 1302-1310.

Dhar, S., Pathak, M. and Shukla, P.R. (2017), "Electric vehicles and India's low carbon passenger transport: a long-term co-benefits assessment", *Journal of Cleaner Production*, Vol. 146, pp. 139-148.

Dietzenbacher, E. and van der Linden, J.A. (1997), "Sectoral and spatial linkages in the EC production structure", *Journal of Regional Science*, Vol. 37 No. 2, pp. 235-257.

Duarte, R., Sanchez-Choliz, J. and Bielsa, J. (2002), "Water use in the Spanish economy: an input-output approach", *Ecological Economics*, Vol. 43 No. 1, pp. 71-85.

EIA (2017), "International energy outlook", US Energy Information Administration, Washington, DC, available at: www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf

Fan, J.-L., Hou, Y.-B., Wang, Q., Wang, C. and Wei, Y.-M. (2016), "Exploring the characteristics of production-based and consumption-based carbon emissions of major economies: a multiple-dimension comparison", *Applied Energy*, Vol. 184, pp. 790-799.

Fan, J.-L., Pan, X. and Li, J.-Q. (2017), "Production-based and consumption-based CO_2 transfers among major economies: a flow chart analysis", *Energy Procedia*, Vol. 105, pp. 3499-3506.

Genty, A., Arto, I. and Neuwahl, F. (2012), "Final Database of Environmental Satellite Accounts: technical report on their compilation", WIOD (World Input-output Database), Vol. Deliverable 4.6, Documentation, pp. 1-69.

Global Energy Network Institute (2006), "Overview of sustainable renewable energy potential of India", available at: www.geni.org/globalenergy/research/renewable-energy-potential-of-india/Renewable%20Energy%20Potential%20for%20India.pdf

Goodman, J. (2016), "The 'climate dialectic' in energy policy: Germany and India compared", *Energy Policy*, Vol. 99, pp. 184-193.

Groenewold, N., Hagger, A.J. and Madden, J.R. (1987), "The measurement of industry employment contribution in an input-output model", *Regional Studies*, Vol. 21 No. 3, pp. 255-263.

Guerra, A. and Sancho, F. (2010), "Measuring energy linkages with the hypothetical extraction method: an application to Spain", *Energy Economics*, Vol. 32 No. 4, pp. 831-837.

He, W., Wang, Y., Zuo, J. and Luo, Y. (2017), "Sectoral linkage analysis of three main air pollutants in china's industry: comparing 2010 with 2002", *Journal of Environmental Management*, Vol. 202, pp. 232-241.

IEA (2016), "World energy outlook", International Energy Agency, available at: www.geni.org/globalenergy/research/renewable-energy-potential-of-india/Renewable%20Energy%20Potential%20for%20India.pdf

IMF (2018), "World economic outlook database", International Monetary fund, available at: www.imf.org/external/pubs/ft/weo/2018/01/weodata/weoselco.aspx?g=2001&sg=All+countries

Jindal, R., Kerr, J. and Nagar, S. (2007), "Voluntary carbon trading: potential for community forestry projects in India", *Asia-Pacific Development Journal*, Vol. 14 No. 2, pp. 107-126.

Kucukvar, M., Egilmez, G., Onat, N.C. and Samadi, H. (2015), "A global, scope-based carbon footprint modeling for effective carbon reduction policies: lessons from the Turkish manufacturing", *Sustainable Production and Consumption*, Vol. 1, pp. 47-66.

Kumar, A., Prakash, O. and Dube, A. (2017), "A review on progress of concentrated solar power in India", *Renewable and Sustainable Energy Reviews*, Vol. 79, pp. 304-307.

Lenzen, M. (2003), "Environmentally important paths, linkages and key sectors in the Australian economy", *Structural Change and Economic Dynamics*, Vol. 14 No. 1, pp. 1-34.

Leontief, W.W. (1936), "Quantitative input and output relations in the economic system of the United States", *The Review of Economics and Statistics*, Vol. 18 No. 3, pp. 105-125.

Liao, H., Andrade, C., Lumbreras, J. and Tian, J. (2017), "CO_2 emissions in Beijing: sectoral linkages and demand drivers", *Journal of Cleaner Production*, Vol. 166, pp. 395-407.

Liu, J., Wang, R., Yang, J. and Shi, Y. (2010), "The relationship between consumption and production system and its implications for sustainable development of China", *Ecological Complexity*, Vol. 7 No. 2, pp. 212-216.

Malik, L. and Tiwari, G. (2017), "Assessment of interstate freight vehicle characteristics and impact of future emission and fuel economy standards on their emissions in India", *Energy Policy*, Vol. 108, pp. 121-133.

Meller, P. and Marfán, M. (1981), "Small and large industry: employment generation, linkages, and key sectors", *Economic Development and Cultural Change*, Vol. 29, pp. 263-274.

Miller, R. and Blair, P. (2009), *Input-Output Analysis: Foundations and Extensions*, 2nd ed., Cambridge University Press, Cambridge.

Miller, R.E. and Lahr, M.L. (2001), "A taxonomy of extractions", in Miller, R.E. and Lahr, M.L. (Eds), *Regional Science Perspectives in Economic Analysis*, 1st ed., Elsevier Science, Amsterdam, pp. 407-441.

Ministry of Environment, Forest and Climate Change (2015), "India's intended nationally determined contributions – towards climate justice", available at: http://envfor.nic.in/sites/default/files/press-releases/revised%20PPT%20Press%20Conference%20INDC%20v5.pdf

Ministry of Environment, Forest and Climate Change (2019), "About the ministry", available at: http://moef.gov.in/about-the-ministry/introduction-8/

Ministry of Power (2018), "Power sector at a glance ALL India", available at: https://powermin.nic.in/en/content/power-sector-glance-all-india

Mishra, M.K., Khare, N. and Agrawal, A.B. (2015), "Scenario analysis of the CO_2 emissions reduction potential through clean coal technology in India's power sector: 2014-2050", *Energy Strategy Reviews*, Vol. 7, pp. 29-38.

Mittal, S., Dai, H., Fujimori, S. and Masui, T. (2016), "Bridging greenhouse gas emissions and renewable energy deployment target: comparative assessment of China and India", *Applied Energy*, Vol. 166, pp. 301-313.

Mohan, R.R. (2018), "Time series GHG emission estimates for residential, commercial, agriculture and fisheries sectors in India", *Atmospheric Environment*, Vol. 178, pp. 73-79.

Morrow, W.R., III Hasanbeigi, A., Sathaye, J. and Xu, T. (2014), "Assessment of energy efficiency improvement and CO_2 emission reduction potentials in India's cement and iron and steel industries", *Journal of Cleaner Production*, Vol. 65, pp. 131-141.

Pal, D. and Mitra, S.K. (2017), "The environmental Kuznets curve for carbon dioxide in `India and China: growth and pollution at crossroad", *Journal of Policy Modeling*, Vol. 39 No. 2, pp. 371-385.

Paladugula, A.L., Kholod, N., Chaturvedi, V., Ghosh, P.P., Pal, S., Clarke, L., Evans, M., Kyle, P., Koti, P. N., Parikh, K., Qamar, S. and Wilson, S.A. (2018), "A multi-model assessment of energy and emissions for India's transportation sector through 2050", *Energy Policy*, Vol. 116, pp. 10-18.

Pappas, D., Chalvatzis, K.J., Guan, D. and Ioannidis, A. (2018), "Energy and carbon intensity: a study on the cross-country industrial shift from China to India and SE Asia", *Applied Energy*, Vol. 225, pp. 183-194.

Perobelli, F.S., Faria, W.R. and Vale, V. D A. (2015), "The increase in Brazilian household income and its impact on CO_2 emissions: evidence for 2003 and 2009 from input-output tables", *Energy Economics*, Vol. 52, pp. 228-239.

Pradhan, B.K., Ghosh, J., Yao, Y.-F. and Liang, Q.-M. (2017), "Carbon pricing and terms of trade effects for China and India: a general equilibrium analysis", *Economic Modelling*, Vol. 63, pp. 60-74.

Raghuvanshi, S.P., Chandra, A. and Raghav, A.K. (2006), "Carbon dioxide emissions from coal based power generation in India", *Energy Conversion and Management*, Vol. 47 No. 4, pp. 427-441.

Ramachandra, T., Aithal, B.H. and Sreejith, K. (2015), "GHG footprint of major cities in India", *Renewable and Sustainable Energy Reviews*, Vol. 44, pp. 473-495.

Ramachandra, T.V., Bajpaia, V., Kulkarnia, G., Aithalae, B.H. and Han, S.S. (2017), "Economic disparity and CO_2 emissions: the domestic energy sector in greater Bangalore, India", *Renewable and Sustainable Energy Reviews*, Vol. 67, pp. 1331-1344.

S.Parikh, K. and K.Parikh, J. (2016), "Realizing potential savings of energy and emissions from efficient household appliances in India", *Energy Policy*, Vol. 97, pp. 102-111.

Sajid, M.J., Cao, Q. and Kang, W. (2019b), "Transport sector carbon linkages of EU's top seven emitters", *Transport Policy*, Vol. 80, pp. 24-38.

Sajid, M.J., Li, X. and Cao, Q. (2019a), "Demand and supply-side carbon linkages of Turkish economy using hypothetical extraction method", *Journal of Cleaner Production*, Vol. 228, pp. 264-275.

Sajid, M.J., Shahni, N. and Ali, M. (2019c), "Calculating inter-sectoral carbon flows of a mining sector via hypothetical extraction method", *Journal of Mining and Environment*, Vol. 10, pp. 853-867.

Schultz, S. (1977), "Approaches to identifying key sectors empirically by means of input-output analysis", *The Journal of Development Studies*, Vol. 3, pp. 77-96.

Singh, K. (2011), "India's emissions in a climate constrained world", *Energy Policy*, Vol. 39 No. 6, pp. 3476-3482.

Sinha, A. and Shahbaz, M. (2018), "Estimation of environmental Kuznets curve for CO_2 emission: role of renewable energy generation in India", *Renewable Energy*, Vol. 119, pp. 703-711.

Song, Y., Liu, C. and Langston, C. (2006), "Linkage measures of the construction sector using the hypothetical extraction method", *Construction Management and Economics*, Vol. 24 No. 6, pp. 579-589.

Stern, D.I. and Jotzo, F. (2010), "How ambitious are China and India's emissions intensity targets", *Energy Policy*, Vol. 38 No. 11, pp. 6776-6783.

Strassert, G. (1968), "Zur bestimmung strategischer sektoren mit hilfe von input-output modellen", *Jahrbucher Fur Nationalokonomie Und Statistick*, Vol. 182, pp. 211-215.

Sun, C., Ding, D. and Yang, M. (2017), "Estimating the complete CO_2 emissions and the carbon intensity in India: from the carbon transfer perspective", *Energy Policy*, Vols 418/427, p. 109.

The Outlook for Energy (2016), "The outlook for energy: a view to 2040", Exxon Mobil Corporation, TX, available at: https://cdn.exxonmobil.com/~/media/global/files/outlook-for-energy/2016/2016-outlook-for-energy.pdf

The World Bank (2018), "The world bank (data) and world development indicators", available at: https://data.worldbank.org

Tian, X., Chang, M., Tanikawa, H., Shi, F. and Imura, H. (2012), "Regional disparity in carbon dioxide emissions", *Journal of Industrial Ecology*, Vol. 16 No. 4, pp. 612-622.

Tian, J., Lumbreras, J., Andrade, C. and Liao, H. (2017), "Key sectors in carbon footprint responsibility at the city level: a case study of Beijing", *International Journal of Climate Change Strategies and Management*, Vol. 9 No. 6, pp. 749-776.

Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R. and de Vries, G.J. (2015), "An illustrated user guide to the world input-output database: the case of global automotive production", *Review of International Economics*, Vol. 23 No. 3, pp. 575-605.

Tortajada, C. and Saklani, U. (2018), "Hydropower-based collaboration in South Asia: the case of India and Bhutan", *Energy Policy*, Vol. 117, pp. 316-325.

United Nations (2017), "World population prospects: the 2017 revision, key findings and advance tables", Department of Economic and Social Affairs, Population Division, Working Paper No. ESA/P/WP/248.

Wang, H., Ang, B. and Su, B. (2017b), "A Multi-Region structural decomposition analysis of global CO_2 emission intensity", *Ecological Economics*, Vol. 142, pp. 163-176.

Wang, Y., Lai, N., Mao, G., Zuo, J., Crittenden, J., Jin, Y. and Moreno-Cruz, J. (2017a), "Air pollutant emissions from economic sectors in China: a linkage analysis", *Ecological Indicators*, Vol. 77, pp. 250-260.

Wang, Y., Wang, W., Mao, G., Cai, H., Zuo, J., Wang, L. and Zhao, P. (2013), "Industrial CO_2 emissions in China based on the hypothetical extraction method: linkage analysis", *Energy Policy*, Vol. 62, pp. 1238-1244.

Yale Center for Environmental Law and Policy (2018), "2018 environmental performance index", Yale University and Center for International Earth Science Information Network, Columbia University, available at: https://epi.envirocenter.yale.edu/downloads/epi2018policymakerssummaryv01.pdf

Zhang, Y. (2010), "Supply-side structural effect on carbon emissions in China", *Energy Economics*, Vol. 32 No. 1, pp. 186-193.

Zhang, Y.-J., Bian, X.-J. and Tan, W. (2017b), "The linkages of sectoral carbon dioxide emission caused by household consumption in China: evidence from the hypothetical extraction method", *Empirical Economics*, Vol. 54 No. 4, pp. 1743-1775.

Zhang, J., Yu, B., Cai, J. and Wei, Y.-M. (2017a), "Impacts of household income change on CO_2 emissions: an empirical analysis of China", *Journal of Cleaner Production*, Vol. 157, pp. 190-200.

Zhao, Y., Liu, Y., Wang, S., Zhang, Z. and Li, J. (2016), "Inter-regional linkage analysis of industrial CO_2 emissions in China: an application of a hypothetical extraction method", *Ecological Indicators*, Vol. 61, pp. 428-437.

Zhao, Y., Zhang, Z., Wang, S., Zhang, Y. and Liu, Y. (2015), "Linkage analysis of sectoral CO_2 emissions based on the hypothetical extraction method in South Africa", *Journal of Cleaner Production*, Vol. 103, pp. 916-924.

Further reading

Nath, A.J., Sileshi, G.W. and Das, A.K. (2018), "Bamboo based family forests offer opportunities for biomass production and carbon farming in North East India", *Land Use Policy*, Vol. 75, pp. 191-200.

Pragya, N., Sharma, N. and Devnekar, A.E. (2017), "Estimation of carbon emissions/savings incurred by wasteland and abandoned cropland-conversion from plantation of biofuel producing perennial tree species - Case study of India", *Global Ecology and Conservation*, Vol. 11, pp. 158-164.

Appendix

Blocks	AHF	MQ	FBT	MR	FC	ME	EGW	CON	TC	MS	Y	X
AHF	25,765	1	44,204	12,763	645	54	11	5,419	2,854	10,998	170,781	273,495
MQ	0	38	63	9,966	14,749	74	3,540	0	8	7	12,880	41,326
FBT	1,302	73	14,333	1,390	2,239	298	88	300	179	5,250	101,654	127,107
MR	1,298	1,265	5,190	95,198	5,714	39,264	817	70,448	11,755	5,125	194,861	430,940
FC	8,119	1,414	3,548	23,739	30,891	3,949	6,022	12,461	42,408	6,748	58,859	198,165
ME	784	1,064	1,065	7,756	1,243	21,967	1,874	5,716	10,309	1,962	133,566	187,309
EGW	2,582	851	1,132	16,128	4,989	3,403	13,562	4,595	4,527	2,071	11,282	65,127
CON	2,216	1,361	1,438	5,949	2,149	2,815	1,903	12,988	7,040	13,530	246,441	297,854
TC	6,977	876	11,172	31,097	20,489	12,780	3,369	18,589	15,018	18,773	103,321	242,480
MS	8,978	1,830	17,885	47,449	33,450	27,403	6,400	27,673	24,201	46,683	482,044	724,165

Notes: Due to non-availability of environmental accounts, intermediate linkages of "private households with employed persons" for accuracy and in accordance with generally accepted approach were removed without sacrificing total economic output of other sectors. While due to lack of intermediate matrices of "public admin and defence; compulsory social security" was also not included in above mentioned classification

Table AI.
Aggregated industrial block input-output table for 2009 (millions of US$)

Code	Our classification	Code	Classification by WIOD
AHF	Agriculture, hunting, forestry and fishing	*AtB*	*Agriculture, hunting, forestry and fishing*
MQ	Mining and quarrying	*C*	*Mining and quarrying*
FBT	Food, beverages and tobacco	*15t16*	*Food, beverages and tobacco*
MR	Manufacturing and recycling	*17t18; 19; 20; 21t22; 25; 26; 27t28; and 36t37*	*Textiles and textile products; leather, leather and footwear; wood and products of wood and cork; pulp, paper, paper, printing and publishing; rubber and plastics; other non-metallic mineral; basic metals and fabricated metal; manufacturing and nec; and recycling*
FC	Fuel and chemicals	*23; and 24*	*Coke, refined petroleum and nuclear fuel; and chemicals and chemical products*
ME	Machinery and equipment	*29; 30t33; and 34t35*	*Machinery and Nec; electrical and optical equipment; and transport equipment*
EGW	Electricity, gas and water supply	*E*	*Electricity, gas and water supply*
CON	Construction	*F*	*Construction*
TC	Transport and communication	*60; 61; 62; 63; and 64*	*Inland transport; water transport; air transport; other supporting and auxiliary transport activities; activities of travel agencies; and post and telecommunications*
MS	Misc. services	*50; 51; 52;J;70; 71t74; L; M; N; and O*	*Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel; wholesale trade and commission trade, except of motor vehicles and motorcycles; retail trade, except of motor vehicles and motorcycles; repair of household goods; hotels and restaurants; financial intermediation; real estate activities; renting of M&Eq and other business activities; education; health and social work; and other community, social and personal services*

Table AII.
Classification of industrial blocks

Corresponding author
Qingren Cao can be contacted at: caoqingren@163.com