Crowding-out of National Energy Consumption Using the Hefty Network of Trade-induced Spillover and Feedback Effects: A Structural Decomposition Analysis

Suvajit Banerjee[1]

Abstract

The study presents a comparative static analysis on the determination of the national energy savings through the routes of the trade-induced spillover and feedback effects. The study constructs an Interregional Input-Output (IRIO) model consisting of the top three carbon emitter economies, namely China, the USA and India and adopts a structural decomposition analysis (SDA). Based on the direction of empirical results from the SDA, the study also explores a couple of simulation-based scenarios assuming a three-country energy-saving climate pact. The simulated scenarios reveal the role of carbon-constraining initiatives by the non-free-rider economies on the final demand-induced national energy consumption of the free-rider economy through the inter-country energy-saving loops. The results substantiate that the USA under both simulated scenarios saves aggregate energy use by outsourcing its production to China and India. On the other hand, China found saving energy usage of the outsourced energy requirement of India and the USA by 0.127% and 0.078% respectively. Here, India is found to save energy as a non-free-rider economy, whereas fails to save energy through outsourcing as a free-rider.

Key-words

National Energy-saving; Spillover Effect; Feedback Effect; Carbon-constraining initiatives; Structural Decomposition Analysis (SDA); Interregional Input-Output Analysis (IRIO)

1. Introduction

According to the Global Energy and CO2 Status Report, 2019, China, the USA and India stand top three positions for their total carbon-dioxide emissions in the year 2018 (IEA, 2019). In 2018, the global energy-related CO_2 emissions rose by 1.7% annual growth rate to a historic high of 33.1 gigatonnes where China, USA and India are accounted for around 85% of the net increase in emissions (IEA, 2019). Interestingly, China, the USA and India are also leading the trend in deploying the renewable energy generation capacity in the world (IEA, 2017). According to the Renewables 2021 Report (IEA, 2021), China will eventually overshoot its current targets for 2030 of 1200 GW of total wind and solar PV capacity before

[1] Visiting Scholar, Centre for Research on Infrastructure Development and Policy (CRIDP), Hyderabad, India. Email: suva.bn1983@gmail.com

2026 to set the stage for a more ambitious renewables growth trajectory for achieving committed carbon-neutrality before 2060. This report also states that the renewable capacity is growing faster in India compared to any other key market in the world relative to its existing capacity with new installations set to double over the forecast period compared with 2015-20 (Ghosh and Banerjee, 2022). For the USA, the expansion of renewable capacity is 65% greater over the forecast period 2021-26 compared to the previous five years (IEA, 2021).

International trade has a significant role in reordering the national energy use patterns of countries (Banerjee, 2019; Banerjee et al., 2021a). Some studies already argued that unilaterally emerged energy-saving initiatives cannot sufficiently achieve the Paris climate goals settled at the 21st Conference of Parties (COP21) meeting in Paris in 2015 (Banerjee, 2020; 2021b; 2021c; Balsalobre-Lorente et al., 2020). According to an International Energy Agency (IEA) report, the $C0_2$ emissions stagnated during 2014-16 with continuous global economic expansion due to steeply increasing energy efficiency and low-carbon technology deployment of some major economies leading to an overall decline in the demand for emission-intensive solid fossil fuels, whereas, this decoupling dynamics largely interrupted in 2017 and 2018 when these low-carbon initiatives could not be scaled up universally across all countries to meet the increasing economic activities (IEA, 2019). Therefore, even achieving a net-zero carbon emission target by a handful of countries in an isolated way cannot ideally ensure the reduction in the aggregate energy use of the entire region or group of trade partners to which these countries belong to. This is because, by the outsourcing of production of final commodities from the backward supply chain, any concerned country can waive its committed reduction in emissions which would create an energy leakage elsewhere (Aichele and Felbermyr, 2015).

Besides competing on the aspects of energy use and carbon emissions, China, India and the USA have intense international trade relationships[2] (Singh and Singh, 2022). The study presents a comparative static analysis on the role of international trade in determining the national energy savings through the routes of the trade-induced spillover and feedback effects (Singh and Singh, 2020; Chen et al., 2021). Economic growth leads to increased demand for final commodities that impels increased economy-wide production activities. With a brawny and exquisite trade linkage of the present world, these increased production activities create a positive spillover effect on the production activities of the connected external economies. On the other hand, these external economies are also having economic dependence on the country which initially experienced an economic growth. Therefore, the initially growing country will further grow with a feedback impact to deliver a required supply of inputs to the connected external economies so that these external economies can contribute to the spillover effect induced supply chain for the original growing country. In this way, for an intensely inter-connected group of economies, the heavy flow of embodied energy is irradiated due to international spillover and feedback effects.

To address the aspects of spillover and feedback effects, the study adopts a structural decomposition analysis (SDA). The SDA is recognised in the literature as a robust and comprehensive methodology from the domain of input-output analysis for addressing the

[2] From the *ITC calculations on the UN COMTRADE statistics*, for instance, in 2018, the shares of export to the USA and India in the total exports of China constitute 19.2% and 3.08% respectively. On the other hand, these volumes of trade constitute around 21.56% and 14.50% of the total import from China by the USA and India respectively. In 2018, India exports 15.98% and 5.09% of its exports to the USA and China respectively and imports 14.50% and 6.44% from China and the USA respectively. For the USA, import and export from China constitute 21.56% and 7.21% respectively, while that from India constitute only 2.16% and 2.01% respectively.

contributions of the inherent socio-economic variables to a change in an aggregate value (Dietzenbacher and Los, 1998; Dietzenbacher and Hoekstra, 2002; Roy et al., 2002; Guan et al., 2008; Su and Ang, 2012). In the energy and environmental analysis as well, the SDA is also acknowledged for offering a broader range of information concerning the technical aspects of energy usage, pollution generation and environmental degradation (Kagawa and Inamura, 2001; Hoekstra and van den Bergh, 2003; Alcántara and Duarte, 2004; Okushima and Tamura, 2007; Zhang, 2010; Butnar and Llop, 2011). The SDA is applied both in the single region-based researches (Wood, 2009; Lim et al., 2009; Yamakawa and Peters, 2011; Su et al., 2017; Banerjee, 2022) as well as multi-region analysis (Brizga et al., 2014; Su and Ang, 2017; Wang et al., 2017; Wang and Liu, 2020; Sesso et al., 2020). SDA is also found applied to explore the individual energy and environmental perspectives of China (Wei et al., 2016; Chang and Lahr, 2016; Yuan et al., 2019; Cao et al., 2019; Wang et al., 2019), the USA (Casler and Rose, 1998) and India (Tandon and Ahmed, 2016; Zhu et al., 2018; Wang and Liu, 2020; Banerjee, 2022). Some other researches explored the driving forces of energy and emissions embodied in the international trade between major economies (Xu and Dietzenbacher, 2014; Su and Ang; 2017; Chen et al., 2019). However, an SDA-based exercise is never seen so far in an interregional format that covers major energy-consuming nations. This study uniquely represents the China-USA-India model intensely connected through international trade as an interregional network of hefty energy flows. The study is the first of its kind where on the one hand, a hybrid-units-based interregional input-output framework is set up to consider the scientific approach of energy transformation and usage, on the other hand, the comparative static frameworks of external impacts on the national energy inventory is elaborated to understand the roles of structurally decomposed drivers of increased energy use.

The study is structured as follows. In the next section, a theoretical framework is built based on the concept of the input-output model. Section 3 elaborates on the methodologies adopted and the database used in the study. Section 4 explains the outcomes of the conducted empirical exercises. Finally, section 5 concludes the paper with some important implications.

2. Theoretical IRIO Framework

The study adopts an algebraic model based on Interregional Input-Output (IRIO) approach suggested in Miller and Blair (2009). The ordinary input-output model adopts the following equation:

$$X = Z + f \quad (1)$$

where X is the vector of gross outputs of different commodities of any defined region and f is the vector of final demands of those commodities of the same region. Here, Z stands as the matrix of intermediate demand of commodities which is assumed to have a fixed proportion of the gross output.

Therefore, $X = (I - A)^{-1} f = Lf$ (2)

where $Z = AX$ and consider $L = (I - A)^{-1}$

Here, A is defined as the matrix of production coefficients (or more formally, technical coefficients). The bracketed inverse term in equation (2) is called the Leontief inverse matrix (L) which corresponds the relationship between the final demand and gross output of the regional economy.

Based on this ordinary input-output formulation, this study adopts the framework of an interregional input-output (IRIO) model. In a 3-region IRIO framework (considering regions c, b and a respectively), Z, f and X are defined as the following:

$$Z = \begin{bmatrix} Z^{cc} & Z^{cb} & Z^{ca} \\ Z^{bc} & Z^{bb} & Z^{ba} \\ Z^{ac} & Z^{ab} & Z^{aa} \end{bmatrix} \quad ; \quad f = \begin{bmatrix} f^c \\ f^b \\ f^a \end{bmatrix} \quad ; \quad X = \begin{bmatrix} X^c \\ X^b \\ X^a \end{bmatrix}$$

From the partitioned matrices of the new Z-matrix, row-wise stand the selling regions and column-wise stand the purchasing regions. With these building blocks, the interregional version of equation (2) would be the following:

$$\begin{bmatrix} X^c \\ X^b \\ X^a \end{bmatrix} = \left\{ \begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} - \begin{bmatrix} A^{cc} & A^{cb} & A^{ca} \\ A^{bc} & A^{bb} & A^{ba} \\ A^{ac} & A^{ab} & A^{aa} \end{bmatrix} \right\}^{-1} \begin{bmatrix} f^c \\ f^b \\ f^a \end{bmatrix} \qquad (3)$$

In the main-diagonal of this interregional A-matrix, the three partitioned matrices stand as the matrix of technical coefficients of the corresponding country c, b and a respectively. On the other hand, the off-diagonal partitioned matrices stand as the matrix of intermediate trade coefficients that reflect the interregional transactions across these three regions.

From equation (3), the aggregate energy consumption (aen) of the three regions can be calculated by pre-multiplying the row-vector of energy-intensities ($\hat{e}$) that consists of energy-intensities of industries of the three corresponding regions.

$$aen = \hat{e} \begin{bmatrix} X^c \\ X^b \\ X^a \end{bmatrix} = (\hat{e}\check{L}) \begin{bmatrix} f^c \\ f^b \\ f^a \end{bmatrix} = \hat{v} f \qquad (4)$$

where $\check{L}$ is the counterpart of the Leontief inverse matrix of equation (2) in the interregional framework. $\hat{e} = [e^c \quad e^b \quad e^a]$ consists of industry-wise energy intensities of the three countries. In equation (4), the term $\hat{v}$ corresponds the interregional energy requirement multiplier that defines the relationship between the final demand and aggregate energy requirement of the three regions.

Consider, between two time-points 0 and 1, the aggregate energy consumption is changing.

$$\Delta aen = aen^1 - aen^0 = \hat{v}^1 f^1 - \hat{v}^0 f^0 = \Delta aen_{\hat{v}} + \Delta aen_f \qquad (5)$$

Equation (5) shows the change in the aen as the sum of the contributions of the change in the energy requirement multiplier and the change in the final demand.

Now, assuming that the final demand is changing for only one region keeping the same final demand for the other two regions, we get:

$$\Delta aen^a = \Delta aen^a_{\hat{v}^a} + \Delta aen^a_f \qquad \text{where } \Delta f = \begin{bmatrix} 0 \\ 0 \\ \Delta f^a \end{bmatrix} \qquad (6)$$

$$\Delta aen^b = \Delta aen^b_{\hat{v}^b} + \Delta aen^b_f \qquad \text{where } \Delta f = \begin{bmatrix} 0 \\ \Delta f^b \\ 0 \end{bmatrix} \qquad (7)$$

$$\Delta aen^c = \Delta aen^c_{\hat{v}^c} + \Delta aen^c_f \qquad \text{where } \Delta f = \begin{bmatrix} \Delta f^c \\ 0 \\ 0 \end{bmatrix} \qquad (8)$$

Now, based on some international treaty, suppose these countries are agreed to reduce energy consumption to relieve emission footprints of the respective economies. With prudent energy-saving initiatives, the energy-intensities in the production of commodities and the resource efficiencies of the technologies in use would help reduce the aggregate energy requirement of all three economies. Now the contribution of the interregional energy requirement multiplier ($\Delta aen_{\hat{v}}$) to the aggregate energy requirement of the three regions as shown in equation (5) is the result of the joint contributions from interregional energy-intensity factor ($\hat{e}$) and interregional technology factor ($\check{L}$). Therefore, the adoption of an energy-saving agreement delivers a dampening impact due to the negative contribution of the interregional energy requirement multiplier on the final demand induced increased total energy requirement.

$$\Delta aen - \Delta aen_f = \Delta aen_{\hat{v}} \qquad \text{such that } \Delta aen_{\hat{v}} < 0 \tag{9}$$

However, if any one of these countries would act like a free rider and does not adopt strict initiatives, the contribution of the aggregate energy requirement multiplier would be weakened. In the presence of a free-rider, the aggregate energy requirement multiplier would still help reduce the total energy requirement induced from the increased final demand of the free-rider country due to interregional feedback impact across the three regions.

$$\Delta aen^a - \Delta aen^a_{f^a} = \Delta aen^a_{\hat{v}^a} \tag{10}$$

$$\Delta aen^b - \Delta aen^b_{f^b} = \Delta aen^b_{\hat{v}^b} \tag{11}$$

$$\Delta aen^c - \Delta aen^c_{f^c} = \Delta aen^c_{\hat{v}^c} \tag{12}$$

Decomposing the right-hand side of equations (10)-(12), the aggregate contribution of the interregional energy requirement multiplier can be expressed as the sum of individual contributions of the national energy-intensity and technology factors of the three countries.

To address the interregional feedback impact, consider a specific time-point 1 and assume country a as the benchmark free-rider in the three-region interregional set-up. Assume that country a is increasing its final demand to achieve an ambitious macroeconomic objective, while the final demand of country b and country c are remaining the same. Because of the specific time-point, the interregional energy-intensity and Leontief multiplier matrix will remain the same due to the assumption of fixed-proportion production under input-output analysis. Therefore, equation (2) can be reinterpreted as a system of following equations:

$$(I - A^{cc})X^c - A^{cb}X^b - A^{ca}X^a = f^c \tag{13}$$

$$-A^{bc}X^c + (I - A^{bb})X^b - A^{ba}X^a = f^b \tag{14}$$

$$-A^{ac}X^c - A^{ab}X^b + (I - A^{aa})X^a = f^a \tag{15}$$

Consider $\Delta f^c = \Delta f^b = 0$ and $\Delta f^a > 0$

Therefore, following equation (13), $(I - A^{cc})\Delta X^c - A^{cb}\Delta X^b - A^{ca}\Delta X^a = 0$

$$\Rightarrow \Delta X^c = (I - A^{cc})^{-1}A^{cb}\Delta X^b + (I - A^{cc})^{-1}A^{ca}\Delta X^a \tag{16}$$

$$\Rightarrow \Delta X^c = SO^{cb} + SO^{ca} \tag{17}$$

Here, the first term on the right-hand side of equation (16) shows the spillover effect from the increased output of country b as a result of increased output in country a. On the other hand, the second term of equation (16) reflects the spillover effect from increased output in country a due to increased final demand in country a. Therefore, in equation (17), the increased gross output of country c is interpreted as decomposed spillover effects from country b and country a respectively. Considering the first term, $A^{cb}\Delta X^b$ is the increased production of inputs in country c to export to country b to facilitate the production of output in country b. Similarly, $A^{ca}\Delta X^{a}$ reflects the increased production of inputs in country c to export to country a in order to facilitate the production of output in country a. Pre-multiplying these two directly increased input production due to spillover effects in country c by the Leontief multiplier for country c brings the total spillover effect on the gross output of country c.

Again, these spillover effects on the output of country c creates a further feedback impact on the output of country b and country a respectively as shown below. These feedbacks are created to support country c by producing inputs in country b and country a such that country c can produce the inputs for facilitating the production of output in country b and country a respectively.

To facilitate the production of inputs in country c, country b and country a delivers inputs to country c. For the production of these inputs, direct feedback impact is created on the gross output of country b and a in the form of $A^{bc}(I-A^{cc})^{-1}A^{cb}\Delta X^{b}$ and $A^{ac}(I-A^{cc})^{-1}A^{ca}\Delta X^{a}$ respectively. Pre-multiplying these direct feedback impacts by the corresponding country-specific Leontief multipliers brings the total impact of the countries as shown below.

Total feedback impact from c to b: $FB^{bc} = (I-A^{bb})^{-1}A^{bc}(I-A^{cc})^{-1}A^{cb}\Delta X^{b}$ (18)

Total feedback impact from c to a: $FB^{ac} = (I-A^{aa})^{-1}A^{ac}(I-A^{cc})^{-1}A^{ca}\Delta X^{a}$ (19)

Similarly, following equation (14), $(I-A^{bb})\Delta X^{b} - A^{bc}\Delta X^{c} - A^{ba}\Delta X^{a} = 0$

$$\Rightarrow \Delta X^{b} = (I-A^{bb})^{-1}A^{bc}\Delta X^{c} + (I-A^{bb})^{-1}A^{ba}\Delta X^{a} \quad (20)$$

$$\Rightarrow \Delta X^{b} = SO^{bc} + SO^{ba} \quad (21)$$

Here, the first term on the right-hand side of equation (17) shows the spillover effect from the increased output of country c as a result of increased output in country a. On the other hand, the second term of equation (16) reflects the spillover effect from increased output in country a due to increased final demand in country a. Therefore, the increased gross output of country b is interpreted as decomposed spillover effects from country b and country c respectively. Therefore, the corresponding feedback impacts are derived as following below.

Total feedback impact from b to c: $FB^{cb} = (I-A^{cc})^{-1}A^{cb}(I-A^{bb})^{-1}A^{bc}\Delta X^{c}$ (22)

Total feedback impact from b to a: $FB^{ab} = (I-A^{aa})^{-1}A^{ab}(I-A^{bb})^{-1}A^{ba}\Delta X^{a}$ (23)

Now, from equation (15):

$$\Delta X^{a} = (I-A^{aa})^{-1}A^{ac}\Delta X^{c} + (I-A^{aa})^{-1}A^{ab}\Delta X^{b} + (I-A^{aa})^{-1}\Delta f^{a} \quad (24)$$

Substituting the value of ΔX^{c} from equation (16) and ΔX^{b} from equation (20) in equation (24), the change in the gross output of country c can be interpreted as shown in equation (26):

$$\Delta X^{a} = (I-A^{aa})^{-1}\Delta f^{a} + (I-A^{aa})^{-1}A^{ab}(I-A^{bb})^{-1}A^{ba}\Delta X^{a} + (I-A^{aa})^{-1}A^{ac}(I-A^{cc})^{-1}A^{ca}\Delta X^{a} + (I-A^{aa})^{-1}A^{ab}(I-A^{bb})^{-1}A^{bc}\Delta X^{c} + (I-A^{aa})^{-1}A^{ac}(I-A^{cc})^{-1}A^{cb}\Delta X^{b} \quad (25)$$

$$\Rightarrow \Delta X^{a} = L^{aa}\Delta f^{a} + FB^{ab} + FB^{ac} + L^{aa}A^{ab}SO^{bc} + L^{aa}A^{ac}SO^{cb} \quad (26)$$

where $L^{aa} = (I-A^{aa})^{-1}$. Therefore, the first term on the right-hand side of equation (26) represents the output produced domestically (DOM^{aa}) using domestic inputs by country a to respond to increased final demand in country a. Here, the fourth and fifth terms represent the indirect feedback impacts IFB^{abc}, IFB^{acb} on the output of country a due to the spillover effects created in country b via the increased output in country c and the spillover effects created in country c via the increased output in country b respectively.

Therefore, $\Delta X^a = DOM^{aa} + FB^{ab} + FB^{ac} + IFB^{abc} + IFB^{acb}$ (27)

Now, the aggregate energy requirement in country a to produce ΔX^a will be:

$$aen^{1a} = e^a \Delta X^a = e^a DOM^{aa} + e^a FB^{ab} + e^a FB^{ac} + e^a IFB^{abc} + e^a IFB^{acb} \quad (28)$$

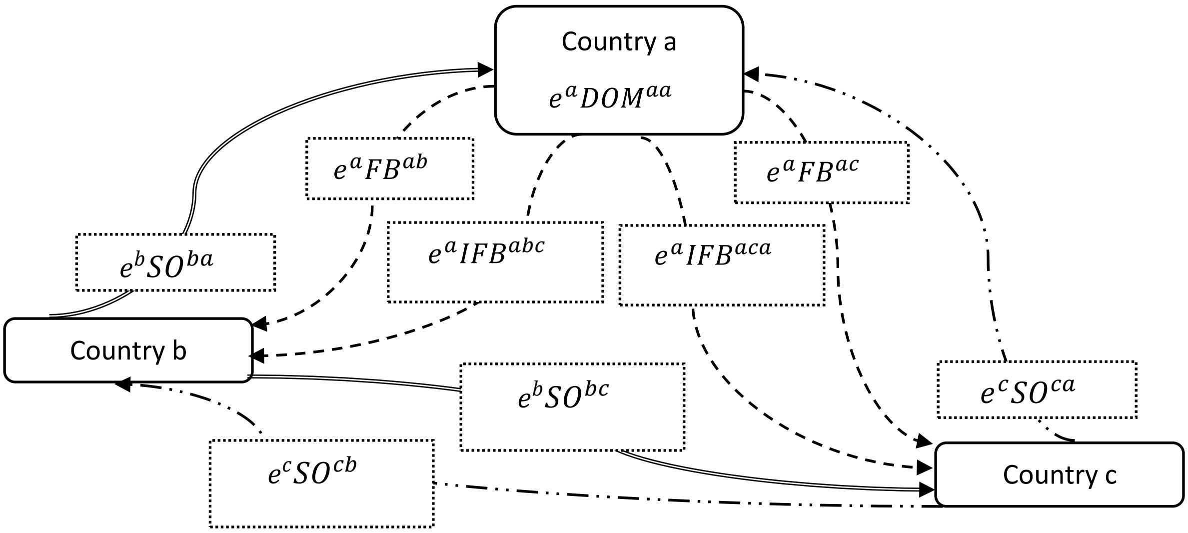
Similarly, the aggregate energy requirement in country b and country c to produce ΔX^b and ΔX^c respectively will be the following:

$$aen^{1b} = e^b \Delta X^b = e^b\, SO^{bc} + e^b SO^{ba} \quad (29)$$

$$aen^{1c} = e^c \Delta X^c = e^c SO^{cb} + e^c SO^{ca} \quad (30)$$

Based on this algebraic model, the complete embodied energy flow in the interregional framework can be graphically portrayed as shown in Figure 1 below.

Figure 1. Flow of Embodied Energy in 3-region Interregional Framework



Source: Authors' Illustration

Therefore, for the free-rider country a, the national energy use with increased final demand without production outsourcing from country b and country c would require the following amount of energy:

$$e^a\{\Delta X^a + \Delta X^b + \Delta X^c\} = e^a DOM^{aa} + e^a FB^{ab} + e^a FB^{ac} + e^a IFB^{abc} + e^a IFB^{acb} + e^a SO^{bc} + e^a SO^{ba} + e^a SO^{cb} + e^a SO^{ca} \quad (31)$$

By out-sourcing of production from country b and country c, total energy savings by country a will be:

$$ENS^a = e^a\{\Delta X^a + \Delta X^b + \Delta X^c\} - e^a \Delta X^a - e^b \Delta X^b - e^c \Delta X^c =$$

$$= (e^a - e^b) SO^{bc} + (e^a - e^b) SO^{ba} + (e^a - e^c) SO^{cb} + (e^a - e^c) SO^{ca} \quad (32)$$

On the other hand, outsourcing of production from country a is creating the spillover effects in country b and country c of the amount ΔX^b and ΔX^c respectively. Now, country b and country c also require international feedback loops in order to deliver the outsourced increased final demand from country a. Therefore, by outsourcing of production, the energy savings by country b and country c will be:

$$ENS^b = (e^b - e^a) FB^{ab} + (e^b - e^a) IFB^{acb} + (e^b - e^c) SO^{cb} \quad (33)$$

$$ENS^c = (e^c - e^a)FB^{ac} + (e^c - e^a)IFB^{abc} + (e^c - e^b)SO^{bc} \quad (34)$$

Therefore, the contribution of the energy-saving inter-country feedback loop to the outsourced national energy use of the three countries can be expressed in the form of following unit-free ratios where the denominators expresses the energy use in the concerned country without dependence on the outsourcing of production of inputs in the backward linked inter-country feedback loop.

$$ENSFL^a = \frac{ENS^a}{e^a\{\Delta X^b + \Delta X^c\}} \quad (35)$$

$$ENSFL^b = \frac{ENS^b}{e^b\{FB^{ab} + IFB^{acb} + SO^{cb}\}} \quad (36)$$

$$ENSFL^c = \frac{ENS^c}{e^c\{FB^{ac} + IFB^{abc} + SO^{bc}\}} \quad (37)$$

3. Methodology and Data

3.1. Hybrid-units IRIO Framework

To hold the fundamental condition of energy conservation, the energy flows in the economy are required to be measured in terms of physical units (Linder and Guan, 2014; Shepard and Pratson, 2020). However, to avoid computational complications of using an entirely physical-unit-based input-output framework in conducting the matrix operations (Pruitichaiwiboon et al., 2011; Brand-Correa et al., 2017), the study adopts a hybrid-units based input-output framework where the energy flows in the economy is measured in physical units (TJ) and the non-energy transactions are measured in value units (Millions of USD). In the IRIO framework, each of the partitioned matrices in the principal diagonal position of the interregional Z matrix is modified in the following way.

$$\dot{Z}^{rr} = \begin{bmatrix} Z_{11}^{rr} & \cdots & Z_{1m}^{rr} & Z_{1,m+1}^{rr} & \cdots & Z_{1n}^{rr} \\ \vdots & \ddots & & & \ddots & \\ Z_{m1}^{rr} & \cdots & Z_{mm}^{rr} & Z_{m,m+1}^{rr} & \cdots & Z_{mn}^{rr} \\ E_{m+1,1}^{rr} & \cdots & E_{m+1,m}^{rr} & E_{m+1,i}^{rr} & \cdots & E_{m+1,q}^{rr} \\ \vdots & \ddots & & & \ddots & \\ E_{n1}^{rr} & \cdots & E_{nm}^{rr} & E_{n,m+1}^{rr} & \cdots & E_{nn}^{rr} \end{bmatrix} = \begin{bmatrix} Z_{m\times m}^{rr} & Z_{m\times q}^{rr} \\ E_{q\times m}^{rr} & E_{q\times q}^{rr} \end{bmatrix} \quad (38)$$

Here, $\dot{Z}^{rr}$ matrix with a '.' on its head is assumed to indicate the transformed hybrid-units matrix corresponding to the value-unit based original matrix. In the hybrid-matrix, the n number of total sectors are arranged by aligning all the m-number of non-energy sectors first, m = 1, …, m, and the remaining q-number of energy sectors at the end q = (m+1), …, n.

Therefore, the transformed Z matrix will be of the following form.

$$\dot{Z} = \begin{bmatrix} \dot{Z}^{PRC-PRC} & \dot{Z}^{PRC-IND} & \dot{Z}^{PRC-USA} \\ \dot{Z}^{IND-PRC} & \dot{Z}^{IND-IND} & \dot{Z}^{IND-USA} \\ \dot{Z}^{USA-PRC} & \dot{Z}^{USA-IND} & \dot{Z}^{USA-USA} \end{bmatrix} \quad (39)$$

Here the three countries are denoted in an abbreviated form such that PRC, IND and USA are indicating the Peoples' Republic of China, India and the United States of America respectively. Similarly, the standard final demand and gross output vectors are also transformed in the following forms.

$$f = \begin{bmatrix} \dot{f}^{PRC} \\ \dot{f}^{IND} \\ \dot{f}^{USA} \end{bmatrix} \quad \text{where } \dot{f}^{r} = \begin{bmatrix} f_1^r \\ \vdots \\ f_m^r \\ f_{m+1}^r \\ \vdots \\ f_n^r \end{bmatrix} \tag{40}$$

$$X = \begin{bmatrix} \dot{X}^{PRC} \\ \dot{X}^{IND} \\ \dot{X}^{USA} \end{bmatrix} \quad \text{where } \dot{X}^{r} = \begin{bmatrix} X_1^r \\ \vdots \\ X_m^r \\ X_{m+1}^r \\ \vdots \\ X_n^r \end{bmatrix} \tag{41}$$

Now, from equation (38), consider the energy-to-energy transformation matrix $E_{q\times q}^{rr}$ of each country as shown below. Suppose the i-st energy sector representing the primary energy and the ii-nd and iii-rd energy sectors representing the useful secondary energy. Besides the primary energy, the secondary energies may be transformed into other types of secondary energies as well. Also, there is certain amount of energy required in each sector as energy industries' own use (EOU). Therefore, besides $\underbrace{EOU}_{ii\to ii}$ amount of own energy requirement, the ii-nd energy sector requires $\underbrace{PRI}_{i\to ii}$ amount of primary energies from the i-th energy sector and $\underbrace{SEC}_{iii\to ii}$ amount of secondary energies from the iii-th energy sector to produce X_{ii}^r amount of useful energies. Similarly, the iii-rd sector requires $\underbrace{PRI}_{i\to iii}$ amount of primary energies from the i-th sector, $\underbrace{SEC}_{ii\to iii}$ amount of secondary energies from the ii-th sector and $\underbrace{EOU}_{iii\to iii}$ amount of own energies for its output production of the amount X_{iii}^r.

$$E_{q\times q}^{rr} = \begin{bmatrix} \underbrace{EOU}_{i\to i} & \underbrace{PRI}_{i\to ii} & \underbrace{PRI}_{i\to iii} \\ 0 & \underbrace{EOU}_{ii\to ii} & \underbrace{SEC}_{ii\to iii} \\ 0 & \underbrace{SEC}_{iii\to ii} & \underbrace{EOU}_{iii\to iii} \end{bmatrix} \tag{42}$$

Based on this energy-to-energy transformation matrix, we construct the matrix of total energy requirement (α-matrix) of the order q-by-n as following below.

$$\alpha = \mathrm{G}\left(\hat{\dot{X}}\right)^{-1}\left(I - \dot{A}\right)^{-1} \tag{43}$$

where $\hat{\dot{X}}$ and $\left(I - \dot{A}\right)^{-1}$ are the hybrid-units interregional gross output vector and Leontief inverse matrix respectively. The α matrix of per-unit total energy requirement shows the energy-variety-wise energy-intensities of all the productive sectors of the economy. The G matrix is constructed whose elements are mostly zeros, the only non-zero elements appear in case, when the energy sector q and industry sector j are the same, however, not a diagonal matrix, since it is not square.

From the α matrix, we define the energy-intensity vector as follows:

$$\hat{e} = i'\,\alpha \tag{44}$$

where i' is a summation vector to operate column sum of α matrix. Here, each element of the $\hat{e}$ vector satisfy the conservation conditions. To accommodate the energy loss during the process of energy conversion we define the non-zero elements in the $\mathrm{G}\left(\hat{\hat{X}}\right)^{-1}$ matrix as the reciprocal of energy conversion efficiencies.

3.2. Hierarchical Structural Decomposition Analysis (SDA)

The study first conducts the structural decomposition exercise of the increased aggregate energy use of top three world emitter economies by following equation (5). In the Level 1 decomposition, the contribution of the total energy requirement multiplier is further decomposed into the contribution of changed energy-intensities and technological change represented by hybrid-Leontief multiplier. The study considers year 2012 as base year time-point '0' and of 2018 as final year time-point '1' as shown in the following equation (45).

$$\Delta aen = aen^1 - aen^0 = \hat{v}^1\dot{f}^1 - \hat{v}^0\dot{f}^0 = e^1\dot{L}^1\dot{f}^1 - \hat{e}^0\dot{L}^0\dot{f}^0 = \Delta aen_{\hat{e}} + \Delta aen_{\dot{L}} + \Delta aen_{\dot{f}} \quad (45)$$

To overcome the biasedness of either base year or final year values, the study follows the criteria of using the average of the base year and final year values as weights of the corresponding contributing variables. To avoid the hybrid-units related computational complications, the study also follows the suggestions proposed in Dietzenbacher and Stage (2006) in the entire decomposition exercise. For the Level 1 decomposition, the following criteria is followed:

$$\Delta aen_{\hat{e}} = \frac{1}{2}\Delta\hat{e}\left(\dot{L}^0\dot{f}^0 + \dot{L}^1\dot{f}^1\right) \quad (46)$$

$$\Delta aen_{\dot{L}} = \frac{1}{2}\left(\hat{e}^0\Delta\dot{L}\dot{f}^1 + \hat{e}^1\Delta\dot{L}\dot{f}^0\right) \quad (47)$$

$$\Delta aen_{\dot{f}} = \frac{1}{2}\left(\hat{e}^0\dot{L}^0 + \hat{e}^1\dot{L}^1\right)\Delta\dot{f} \quad (48)$$

In the subsequent levels of decompositions as well, the study followed these above criteria.

In the Level 2 structural decomposition, the study will be digging deeper into $\Delta\hat{e}$.

From equation (44), we know $\widehat{e^t} = i'\ \alpha^t$ (49)

where t stands for two time-points 0 and 1.

Consider $\beta^t = \alpha^t(e^t)^{-1}$ (50)

where α^t is the diagonal matrix of the $\widehat{e^t}$ vector and β^t is defined as the energy-intensity composition of industries.

Now, substituting α^t from equation (49) with its derived value in equation (50) we get the following.

$$\widehat{e^t} = i'\beta^t e^t = i'\beta^t(\hat{e}^t_{PRC} + \hat{e}^t_{IND} + \hat{e}^t_{USA}) = i'\beta^t\hat{e}^t_{PRC} + i'\beta^t\hat{e}^t_{IND} + i'\beta^t\hat{e}^t_{USA} \quad (51)$$

where $\hat{e}^t_{PRC} = [\hat{e}^t_{PRC} \quad 0 \quad 0]$, $\hat{e}^t_{IND} = [0 \quad \hat{e}^t_{IND} \quad 0]$, $\hat{e}^t_{USA} = [0 \quad 0 \quad \hat{e}^t_{USA}]$

Now, define $y^t_r = \alpha^t_r i$ and $\rho^t_r = (y^t_r)^{-1}\alpha^t_r$ (52)

And assume $\varepsilon^t_r = (\rho^t_r)'$ such that $\varepsilon^t_r = \begin{bmatrix}\varepsilon^t_{PRC}\\ \varepsilon^t_{IND}\\ \varepsilon^t_{USA}\end{bmatrix}$ (53)

where i is the post-multiplier summation vector operator for summing up the rows of the pre-multiplier α_r^t matrix such that r stands for the specific regions of analysis. Therefore, y_r^t representing the summation of industry-wise energy intensities of all the energy varieties and each row of the column vector ε_r^t consisting of elements representing the relative energy-intensities of all energy varieties of any specific industry having its activity in the country r. Therefore, summation of the values of each row of the ε_r^t matrix will be unity.

$$i'\varepsilon_r^t = i' \qquad (54)$$

Substituting i' in equation (51) would give the following.

$$\widehat{e^t} = i'\varepsilon_{PRC}^t\beta^t\hat{e}_{PRC}^t + i'\varepsilon_{IND}^t\beta^t\hat{e}_{IND}^t + i'\varepsilon_{USA}^t\beta^t\hat{e}_{USA}^t \qquad (55)$$

Substituting the value of $\widehat{e^t}$ in equation (45) would give:

$$\Delta aen = aen^1 - aen^0$$

$$=i'\{\Delta\varepsilon_{PRC} + \Delta\beta_{PRC} + \hat{e}_{PRC}\} + i'\{\Delta\varepsilon_{IND} + \Delta\beta_{IND} + \hat{e}_{IND}\} + i'\{\Delta\varepsilon_{USA} + \Delta\beta_{USA} + \hat{e}_{USA}\} + \Delta X \qquad (56)$$

where $\varepsilon_r^t\beta^t\hat{e}_r^t = \varepsilon_r^t\beta_r^t\hat{e}_r^t$

Equation (56) represents the change in aggregate energy use of the three countries during the period of 2012-2018 in terms of the industry-wise and country-wise contributions of the change in relative energy-intensity proportions of the energy varieties ($\Delta\varepsilon$), industry-wise and country-wise contributions of the change in energy-intensity composition of industries ($\Delta\beta$), industry-wise and country-wise contribution of the change in aggregate energy-intensities and the contribution of the change in the aggregate gross output of the three countries.

Now, in the Level 3 structural decomposition, we will be digging deeper into $\Delta\dot{L}$. With matrix formulation, the study follows the following criteria:

$$\Delta\dot{L} = \dot{L}^1\Delta\dot{A}\dot{L}^0 \qquad (57)$$

Considering the column-specific technology change, $\Delta\dot{A}$ from equation (57) can be replaced by additively decomposed country-specific technological coefficient matrices as shown in the following equation (58).

$$\Delta\dot{L} = \dot{L}^1\Delta\dot{A}_{PRC}\dot{L}^0 + \dot{L}^1\Delta\dot{A}_{IND}\dot{L}^0 + \dot{L}^1\Delta\dot{A}_{USA}\dot{L}^0 \qquad (58)$$

Substituting the value of $\Delta\dot{L}$ in equation (45), and conducting structural decomposition exercise following the criteria as shown in the Level 1 Decomposition of equations (46) to (48), we get the Level 3 decomposition result.

$$\Delta aen = aen^1 - aen^0 = \Delta aen_{\hat{e}} + \Delta aen_{\dot{L}PRC} + \Delta aen_{\dot{L}IND} + \Delta aen_{\dot{L}USA} + \Delta aen_{\dot{f}} \qquad (59)$$

For the Level 4 decomposition, we additively decompose equation (40) as follows.

$$\Delta\dot{f} = \begin{bmatrix} \Delta\dot{f}^{PRC} \\ \Delta\dot{f}^{IND} \\ \Delta\dot{f}^{USA} \end{bmatrix} = \begin{bmatrix} \Delta\dot{f}^{PRC} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \Delta\dot{f}^{IND} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \Delta\dot{f}^{USA} \end{bmatrix} \qquad (60)$$

Substituting this value of $\Delta\dot{f}$ in equation (44) and conducting structural decomposition, we get the Level 4 decomposition result.

$$\Delta aen = aen^1 - aen^0 = \Delta aen_{\hat{v}} + \Delta aen_{\dot{f}PRC} + \Delta aen_{\dot{f}IND} + \Delta aen_{\dot{f}USA} \qquad (61)$$

By accommodating all hierarchically decomposed contributions together, the study expresses the increased aggregate energy use of the three countries as following below:

$$\Delta aen = \hat{e}_{PRC} + \hat{e}_{IND} + \hat{e}_{USA} + \Delta aen_{\dot{L}^{PRC}} + \Delta aen_{\dot{L}^{IND}} + \Delta aen_{\dot{L}^{USA}} + \Delta aen_{\dot{f}^{PRC}} + \Delta aen_{\dot{f}^{IND}} + \Delta aen_{\dot{f}^{USA}} \quad (62)$$

3.3. Decomposition of Energy-saving Feedback Loop

The study undertakes the following two simulation-based exercises:

- Simulation 1. The USA increases its final demand of all commodities by 50% of the base-year final demand of 2018 level while the final demand of India and China remained at their 2018 level.
- Simulation 2. India increases its final demand of all commodities by 50% of the base-year final demand of 2018 level while the final demand of the USA and China remained at their 2018 level.

3.4. Database

The study used the ADB-MRIO database for constructing the three-country interregional input-output table consisting of China, India and the USA. For a meaningful structural decomposition, without the influence of inflation, the study used the database at constant prices of 2010 for the years of 2018 and 2012. For the sector-wise energy requirement of the three countries and country-wise energy transformation, the study extracted data from the energy-commodity balance tables of the United Nations Energy Statistics of 2018 Energy Balances and 2012 Energy Balances.

For constructing a hybrid-units IRIO framework, the study arranged 15 non-energy sectors for each of the countries. From the energy balance tables, the study included nine energy sectors in the input-output framework for China and the USA. However, for India, we found no contribution of HEAT in either energy transformation or consumption in the energy-commodity balance table. Therefore, the study includes only eight energy sectors in the case of India. In this way, the study constructed a 71-by-71 hybrid interregional input-output table.

4. Results and Discussions

4.1. Energy-Intensity, Technology and Final Demand

Table 1 is showing the calculated country-wise and sector-wise energy intensities for two years, namely 2012 and 2018. In the first column of this table, the sector details are shown corresponding to the abbreviated short names mentioned in the second column that is used subsequently in the following part. The most prominently observable findings from these calculated energy-intensity values can be listed as follows:

Table 1. Calculated Sector-wise Energy-Intensities of Top Three World Emitters

Sector Details	Sectors	PRC		IND		USA	
		2012	2018	2012	2018	2012	2018
Non-Energy Sectors							
Agriculture, Forestry and Fishing	AGRI	10.31	8.92	14.27	13.46	13.73	13.07
Mining and Quarrying	MINE	9.97	6.98	5.39	6.78	4.35	6.68
Food, Beverages and Tobacco	FOOD	10.05	7.64	14.90	14.90	12.05	13.23
Textiles and Leather	TEXL	11.08	8.97	10.59	9.81	11.39	11.81
Wood and Wood Products	WOOD	10.37	7.97	11.22	17.76	15.04	13.49
Paper, pulp and Printing	PAPE	11.79	8.66	11.45	8.99	8.43	7.72
Chemical, Chemical Products; Rubber and Plastics	CHEM	20.31	13.84	9.79	9.06	6.86	9.06
Non-metallic Minerals	NMET	13.56	8.64	23.50	30.74	23.19	20.69
Basic Metals and Fabricated Metal Products	BMET	36.68	33.19	21.68	16.53	10.59	13.13
Machinery; Electrical and Optical Equipment	MAEQ	15.21	11.61	9.91	7.89	7.84	6.53
Transport Equipment	TREQ	15.68	11.64	10.35	7.92	6.75	6.35
Other Manufacturing, n.e.c.; Recycling; Sales and Maintenance Activities	OTIN	36.99	24.96	26.62	33.49	4.89	4.97
Construction	CONS	16.67	13.19	11.52	10.73	5.92	7.50
All Transportation – Inland, Water, Air and Auxiliary	TRAN	41.29	35.18	20.49	16.38	67.53	65.50
All Services and Public Administration	SERV	8.12	7.56	4.59	5.06	4.51	4.35
Energy Sectors							
Primary Coal, Coke	COAL	1.00	1.00	1.00	1.00	1.00	1.00
Coal Products	CPRO	3.24	2.62	2.45	2.95	5.43	2.80
Crude Petroleum	POIL	1.00	1.04	1.00	1.00	1.00	1.02
Oil Products	OPRO	2.35	2.75	3.18	2.93	2.15	2.62
Natural Gas	NGAS	1.00	1.00	1.00	1.00	1.00	1.10
Biofuels and Waste	BFUE	1.00	1.00	1.00	1.00	1.00	1.00
Nuclear and Other Renewables	NUCL	1.00	1.00	1.00	1.00	1.00	1.00
Electricity	ELEC	5.73	5.02	7.79	6.34	5.51	5.35
Heat	HEAT	3.59	3.02	-	-	5.57	4.35

Note: All units are in Terajoule (TJ) per Million USD

Source: Authors' Calculation

- The energy-intensities of the primary energy sectors are always held unity for each country in both the time-points. Therefore, in this framework, the energy intensity of the five primary energies, namely COAL, POIL, NGAS, BFUE, NUCL are considered as the benchmark energy-intensity values of one Terajoule (hereafter mentioned as TJ) per millions of USD. This is because the energy sources of primary energies are considered exogenous to the system of hybrid-framework transaction table. Among these five primary energy varieties BFUE and NUCL are considered renewable energies.
- The energy-intensities of the four secondary energy varieties, namely CPRO, OPRO, ELEC and HEAT are derived from the unit-valued energy-intensities of the primary energy varieties, original energy-intensities of the other secondary source energy varieties, energy-intensities of the non-energy inputs contributed to the energy processing and the loss of energy during the processing of energy transformation.
- Among the manufacturing activities in the non-energy sectors, the bigger values of the energy-intensities are found in CHEM, NMET, BMET, MAEQ, TREQ and OTIN. Interestingly, the value of these energy intensities is lower in the case of the USA, while they are more significantly dropping in the case of China and India during 2012-2018. In the case of India, an increase in the energy-intensity is found only in MINE, WOOD, NMET, OTIN and SERV, while for the USA, this marginally increased in TEXL and OTIN and significantly increased in MINE, FOOD, CHEM, BMET and CONS. In the case of China, energy-intensity significantly dropped in all the sectors during 2012-18.

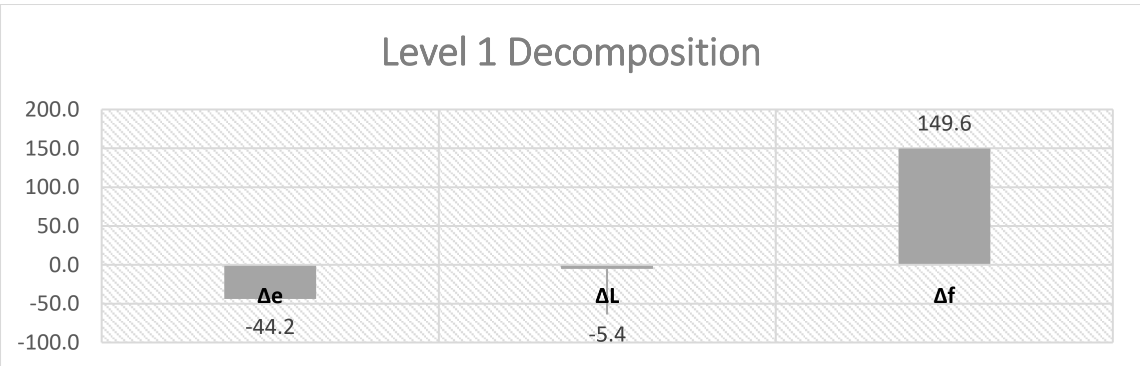
Using the energy-intensities as portrayed in Table 1, the aggregate energy use of the three countries is calculated. The calculated aggregate energy use of the two time-points 2012 and 2018 are shown in Table 2 below. Alongside, Table 2 is also showing that the increase in the aggregate energy use during 2012-18 is 280 288 883.6 TJ.

Table 2. Calculated Aggregate Energy Consumption by Top Three World Emitters (In TJ)

	Total Energy Consumption (TJ)
Year 2012	1289625964.8
Year 2018	1569914847.4
Increased during 2012-2018	280288883.6

Source: Authors' Calculation

Figure 2. Energy-intensity, Technology and Final demand in the Increased Energy Use



Source: Authors' Illustration

From the Level 1 structural decomposition of the increased aggregate energy use, the study expresses the increased energy consumption of the three countries in terms of the contributions of the changed interregional energy-intensity, technology and final demand factors. The result of this Level 1 decomposition is portrayed in Figure 2 above. Figure 2 is showing that increased final demand induced fomented energy use is around 149.6% (aggressively rounded up) of the original increased energy use of the three countries during the period 2012-18. On the other hand, changed interregional energy-intensity and technology are bringing dampening impacts of around 44.2% and 5.4% respectively in the scale-induced and final demand-led energy consumption. The Level 1 decomposition result is giving a snapshot idea of the importance of three major drivers of changed energy use. Taking the three largest carbon-di-oxide emitters together, we found a sharp fall in the sectoral energy-intensities during 2012-18 which is reducing the potential increase in energy consumption by a large extent. Changes in the interregional technical coefficients also changed the interregional Leontief inverse matrix that contributed to the inter-and-intra-sectoral trade and transactions and transformed the technological features of the three countries. The study found this technological change also contributing to a substantial reduction in the potential energy consumption.

4.2. Hierarchical Contributions to Increased Energy Use

After the Level 1 decomposition exercise, the study proceeds to further decompose all three major drivers of increased energy use during the period 2012-18. Figure 3 displays the result of the Level 2 decomposition exercise where the contribution of the changed interregional energy-intensity to the overall changed energy consumption of the three countries is decomposed into the industry-wise and country-wise contributions of the change in relative energy-intensity proportions of the energy varieties ($\Delta\varepsilon$), industry-wise and country-wise contributions of the change in the energy-intensity composition of industries ($\Delta\beta$), industry-wise and country-wise contribution of the change in aggregate energy-intensities ($\Delta\hat{e}$) and the contribution of the change in the aggregate gross output of the three countries (ΔX).

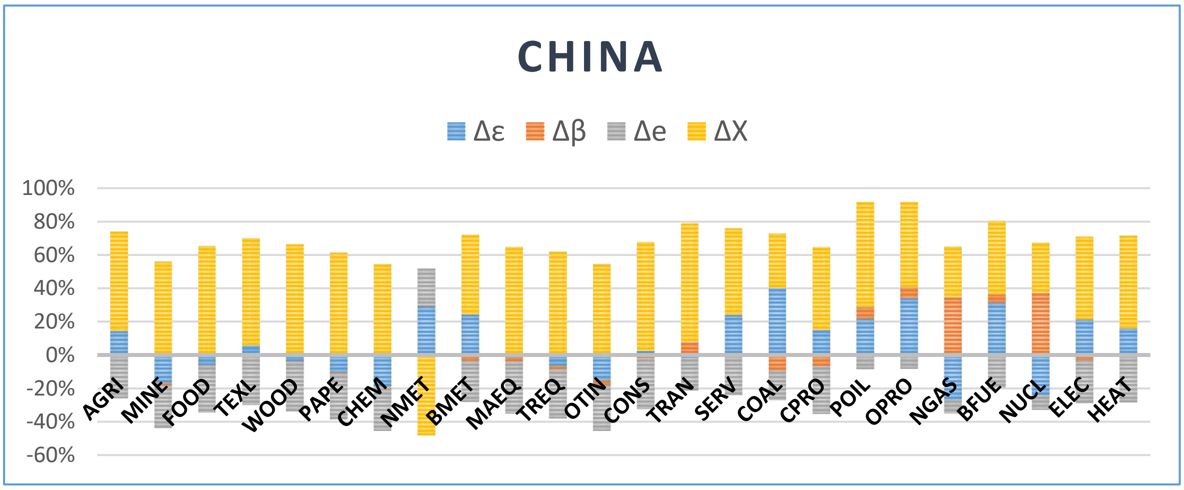
Figure 3 shows the contributions of the $\Delta\varepsilon$ and $\Delta\beta$ using the proportions of the bars corresponding to different sectors coloured in red and blue respectively. As a contributing driver, we found that the changed energy-intensity composition of industries ($\Delta\beta$) is playing a bigger role than the changed relative energy-intensity proportions of the energy varieties ($\Delta\varepsilon$) in reducing the overall energy consumption of India and the USA. While in the case of China, $\Delta\varepsilon$ is pushing the energy intensity downward more prominently than $\Delta\beta$. For the USA, $\Delta\beta$ in most of the sectors is working as a positive contributor of increased energy use. This means that the US industries have become more intensive towards the energy-intensive input options for the production of their outputs. The graph shows that China prudently limited the spread of its emission-intensive and high energy-consuming COAL and CPRO across the industries which helped the corresponding $\Delta\varepsilon$ to reduce energy consumption substantially while the spread of low-emission intensive non-renewable and renewable energies, namely NGAS, BFUE and NUCL increased many times that is reflected in the substantially increased national energy use.

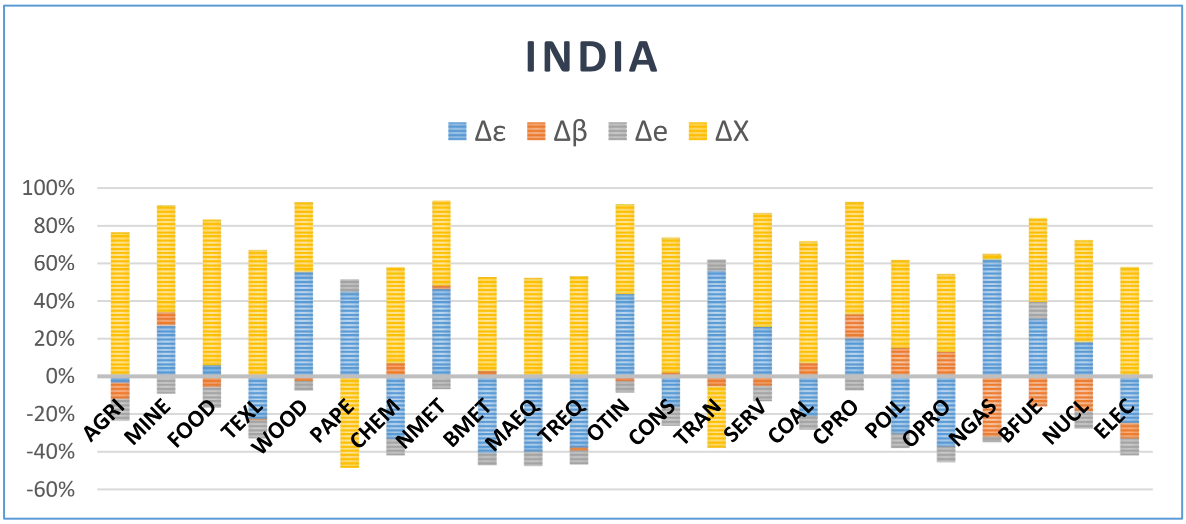
Figure 4 is showing the Level 3 SDA of the contribution of the interregional Leontief multiplier into the national contributions of the change in technical coefficients of the three economies. The figure clearly shows that the dampening impact of the technological change that contributed to the overall change in potential energy consumption as found in the Level 1 decomposition is mostly due to the increased energy-non-intensity in China. The figure shows the individual contributions of the national technologies in the absolute physical unit of energy. In percentage terms, Chinese and Indian technology contributed 92.28% and

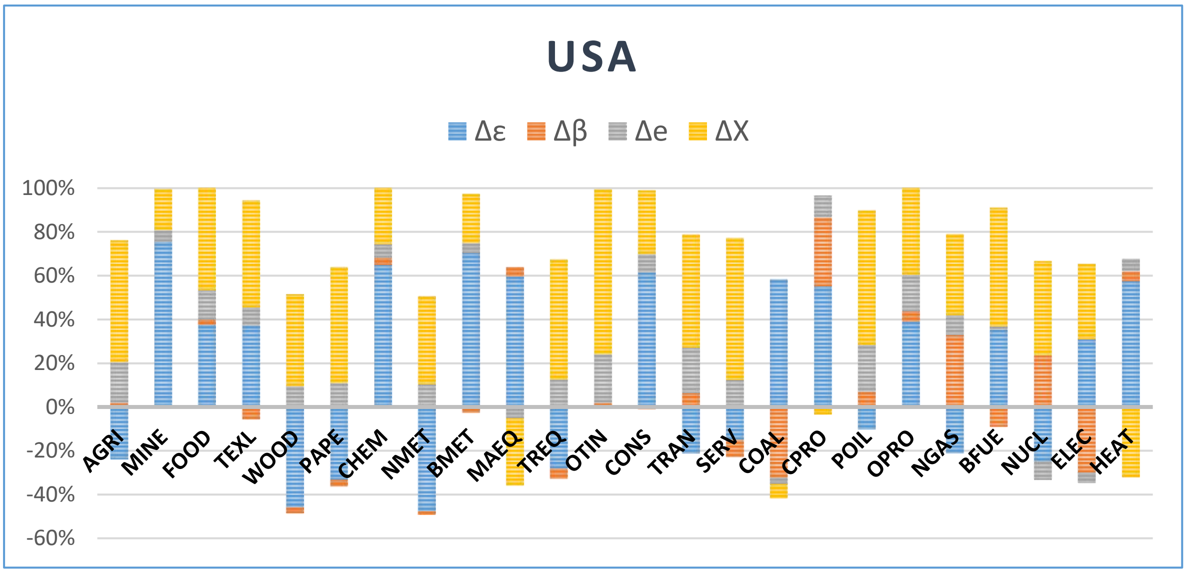
10.25% respectively to the reduction in the overall energy consumption. On the other hand, the technology of the USA in 2018 is found to become more energy-intensive compared to 2012 such that it positively contributed around 2.5% to weaken the dampening impact of the overall technological change.

In the Level 4 decomposition exercise, we distinguished the energy use contribution of the increased final demand into the final demand-led individual national contributions of the three countries. Figure 5 is illustrating the result of this entire hierarchical decomposition exercise in a single graphical representation. We find here that final demand-led increased energy consumption is highest in the case of China, followed by the USA and India. However, in terms of the magnitude of this contribution, China is found far ahead of its nearest competitor in our analysis. Increased final demand over time increases the scale of productive activities in the economy which requires an uninterrupted energy supply. This scale induced energy use for

Figure 3. Structural Decomposition of Country-wise Energy-intensity

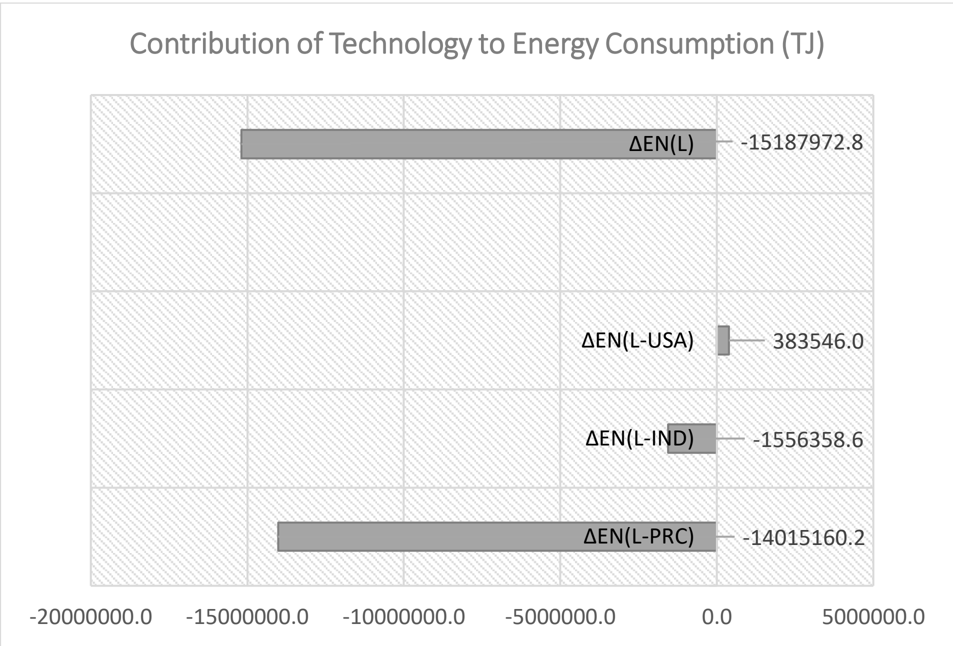






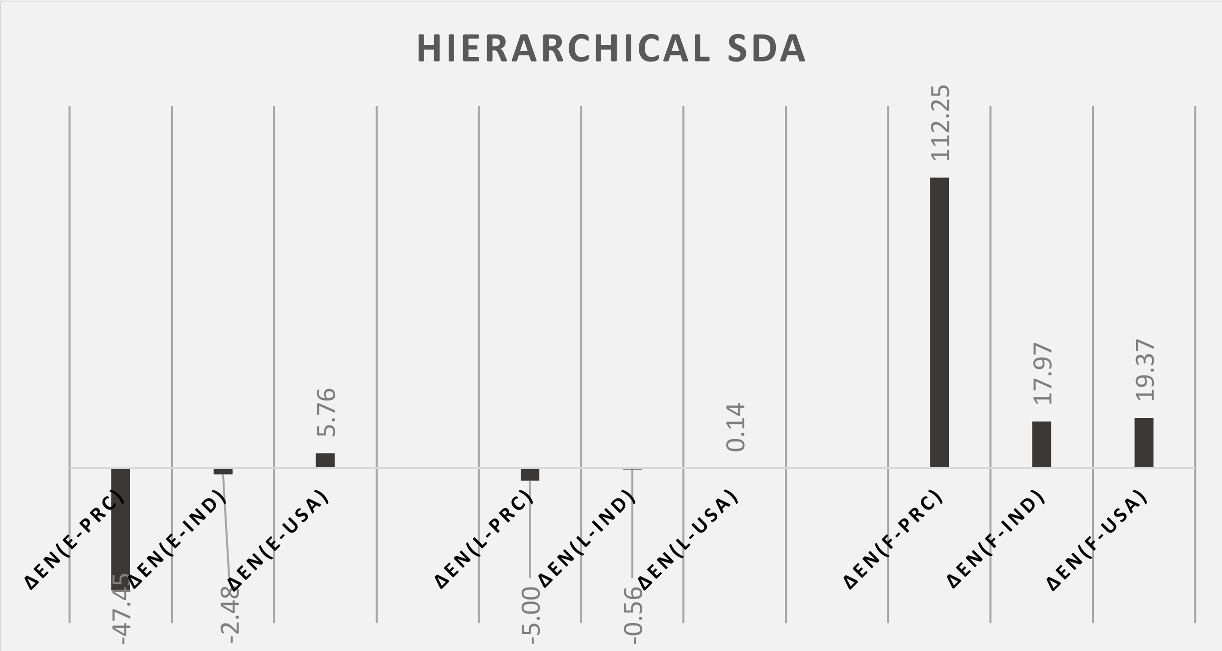
Source: Authors' Illustration

Figure 4. Structural Decomposition of Inter-country Leontief Multiplier



Source: Authors' Illustration

Figure 5. Complete Decomposition of Aggregate Energy Use by Top Three Emitters



Source: Authors' Illustration

China is around 112.25% of the increased original energy consumption of the three countries while for the USA and India these are around 19.37% and 17.97% respectively. In terms of the original change in the aggregate energy use of the three countries, the overtime technological change by China, India and the USA contributed around -5.00%, -0.56% and 0.14% respectively. This means that technology helped significantly in the case of China and marginally in the case of India to reduce the scale induced increased potential energy consumption of the three countries. However, in the case of the USA, technology contributed positively to the potential energy consumption of the three countries. Besides, technology, we found that the changed energy-intensities in the USA are also positively and significantly contributing to the increased potential energy use due to final demand in the three countries. According to the Level 1 decomposition exercise, the changed energy intensity reduced the potential energy consumption by around 44.2%. But in the case of India as well, the changing energy intensities during 2012-2018 only contributed 2.48% to reduce this potential energy consumption. Only, the changed energy intensity of China is found as the major driving force to determine the original increase in the energy use of the three economies.

To analyse the change in the volumes of energy use, Table 3 is showing the energy consumption sizes of the three countries in 2012 and 2018. One interesting finding from this table is that India is rapidly catching up to the USA and China as far as energy use is concerned. In 2012, the energy consumption of China and the USA was 394.6% and 222% higher than that of India respectively, while in 2018 they found higher by 374.7% and 188.7% respectively. This finding is further substantiated from a result shown in the last column of Table 2. According to this result, the increase in the energy use during 2012-2018 as a percentage of energy use of the base year 2012 is highest in the case of India, followed by China and the USA.

Table 3. Country-wise Disaggregated Energy Consumption in 2012 and 2018 (In TJ)

Country Abbreviation	2018		2012		Increased Energy Use during 2012-2018	Increased Energy Use based on 2012 (%)
	Energy Use	% Higher than Indian Level	Energy Use	% Higher than Indian Level		
PRC	863087497.7	374.7	695880223.0	394.6	167207274.7	24.0
IND	181827807.7	0.0	140706397.0	0.0	41121410.7	29.2
USA	524999541.9	188.7	453039343.7	222.0	71960198.2	15.9

Source: Authors' Calculation

Therefore, from the hierarchical SDA, we found that China is both the biggest contributor to the potential interregional energy use and major driving economy to eliminate this scale-driven increased potential energy consumption. On the other hand, the USA found as the worst performer among the three countries in terms of generating dampening impact on the increased potential energy use and India is sharply increasing its energy consumption compared to China and the USA, although contributing to reducing the potential energy consumption to a smaller extent. To understand the roles of these economies and their driving forces we further analysed the interregional energy requirement multiplier.

4.3. Decomposition of Interregional Energy Requirement Multiplier

For the analysis on the role of aggregate energy requirement multiplier ($\hat{v}$), the study assumes that the final demand is changing for only one region in a single scenario as shown in equations (6)-(8) under Section 2. After building scenarios corresponding to the unilaterally increased final demand of the countries, the study conducts a hierarchical SDA following equation (4). In these cases, the aggregate contribution of the final demand to the overall increased energy use is the same contribution of the unilaterally increased final demand of a single country while the final demand contribution of the other two countries become zero.

Table 4 is portraying the results of the SDA conducted in the three scenarios under unilaterally increased final demand of the three countries respectively. The table is showing that during 2012-18, aggregate energy use increased by 176763510.0 TJ under scenario 1, whereas decreased by -64686379.5 TJ and 58003133.7 TJ under scenario 2 and scenario 3 respectively. Of this total change in the aggregate energy use, the contribution of the unilaterally increased final demand and $\hat{v}$ is shown in the last two rows. Under all these scenarios, the $\hat{v}$ contributed as a powerful driver for the savings of potential energy use. The dampening impact of this multiplier is even found overpowering the scale-driven increased energy use in the cases when the impacts of unilaterally increased final demand of China are considered zero. When there is only a unilateral increase in the final demand of China, however, the dampening impact of the multiplier is only 77.98% of the original increased aggregate energy use.

Table 4. Aggregate energy use induced from final demand and energy requirement multiplier

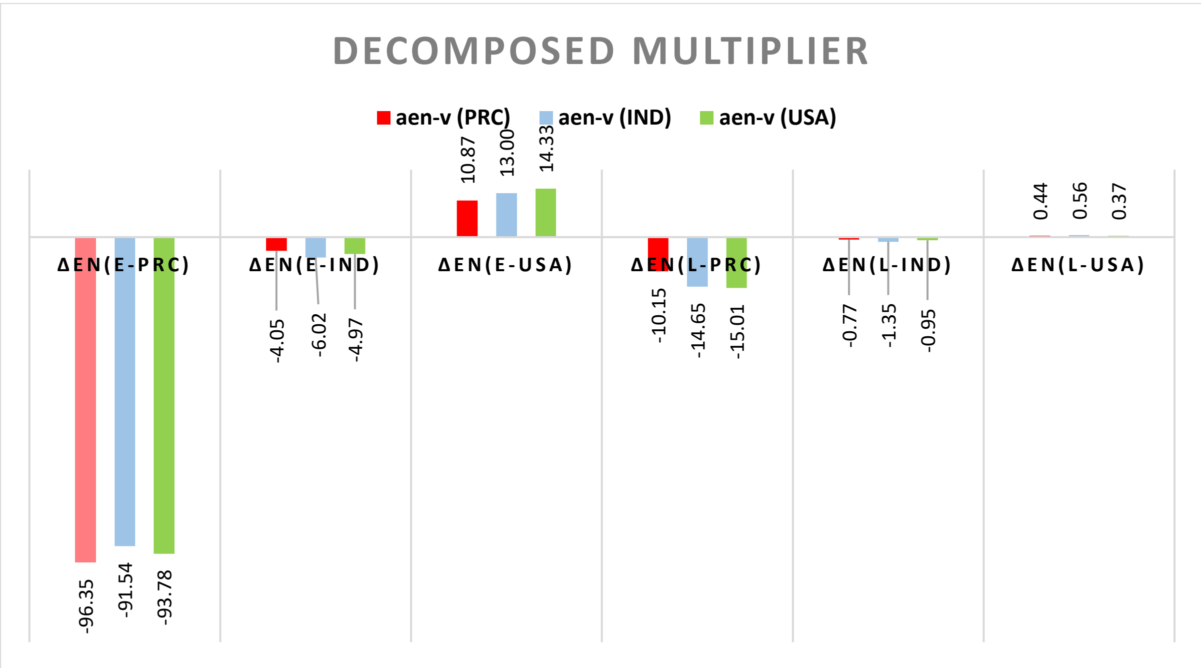
	aen(Δf-PRC)	aen(Δf-IND)	aen(Δf-USA)
aen(2018)	1466389473.8	1224939584.3	1231622830.1
aen(2012)	1289625963.8	1289625963.8	1289625963.8
Δaen	176763510.0	-64686379.5	-58003133.7
Δaen(f)	314616675.5 (177.98)	50362808.1 (77.86)	54281728.5 (93.58)
Δaen(v)	-137853165.4 (-77.98)	-115049187.6 (-177.86)	-112284862.2 (-193.58)

Note: In the parentheses, percentage of Δaen is mentioned.

Source: Authors' Calculation

For a detailed view of the multiplier, we decomposed its contribution in terms of the country-wise contribution of the changing energy intensities and technologies. The result of this level of decomposition is shown in Figure 6. Here, the red, blue and green ribbons indicate the three scenarios in which the unilateral final demand increased for only China, India and the USA respectively. In all three scenarios, the energy-intensity drivers of China are found to significantly reduce the combined energy use of the three countries. China is substantially reducing the potential aggregate energy use in terms of technology as well. Changing energy-intensities of India is also actively participating in the energy use reduction initiatives, while changed production technology of India marginally is helping to reduce the aggregate energy use. On the other hand, the USA is neither technologically nor with energy-non-intensification of the sectors contributed to the reduction of potential energy consumption of the three countries.

Figure 6. Decomposition of Interregional Energy Requirement Multiplier



Source: Authors' Illustration

In the second and third scenarios, when China's final demand is held at the 2012 level, however, technology and energy-intensities are considered at the 2018 level, the updated energy-intensities and technological efficiencies are delivered to overpower the scale-induced increased energy consumption. With increased economic activities to facilitate the production of a gigantic final demand of commodities, China's deployment of renewable energy generation capacity substantially compensating both uninterrupted economic development and reduced fossil-fuel energy intensity (Inglesi-Lotz, 2016; Balsalobre-Lorente et al., 2018; Sharma et al., 2021; Dogan et al., 2021). Therefore, in this IRIO analysis, China is found as the leading force to engage the overall energy-saving initiative.

4.4. The Free-Rider and Inter-country Feedback Loop

The study assumes that the free-rider country does not initiate prudent energy-saving policies rather depends on the outsourcing of a proportion of its production activities required to facilitate the delivery of its unilaterally increased final demand. With a 50% increased final demand, the outsourcing of production from the free-rider country is empirically addressed following the analytical background developed in Section 2. The inter-country complex network is converted into an embodied flow of energy under two different simulation exercises.

In simulation exercise 1 and 2, the USA and India are considered as the free-rider countries respectively[3]. Table 5 shows the calculated contributions of the inter-country spillover and feedback loops in percentage terms to the national energy use of China, India and the USA under simulation exercise 1 and 2. In the first simulation, the spillover effects on China and India contributes in the energy saving from outsourcing of the USA by dampening 86.9% and 12.7% respectively. Here, the indirectly impacted India is also found saving energy due to its feedback and spillover loops. However, the direct feedback from India to the USA and indirect feedback from India to the USA via China are found contributing to negative energy savings which is more than compensated by the spillover effect from India to China which contributed 326.10% of the original energy savings by India. Lastly, in the case of China, we found both India and the USA are contributing with negative energy savings for China. Therefore, this simulation exercise 1 exposes that the USA benefits most out of its trade linkages with China and India in terms of saving energy through outsourcing of production.

In simulation exercise 2, we observe that the energy embodied in the spillover effect from India to the USA is surpassing that from India to China, such that India is ultimately ending up with a negative energy saving. Similar to the first simulation, here also, China experiences negative energy savings. However, being an indirectly impacted economy in this simulation exercise as well, only the USA benefited from the energy saving spillover and feedback loops with China and India. On the other hand, the study found China is worst performed in terms of saving energies through its trade linkages with the India and the USA and as a free-rider India also could not arrange to save energy consumption through inter-country embodied energy flows.

[3] Of these exercises, the flow of energy embodied in the more energy-intensive sectors are illustrated graphically in the Appendix.

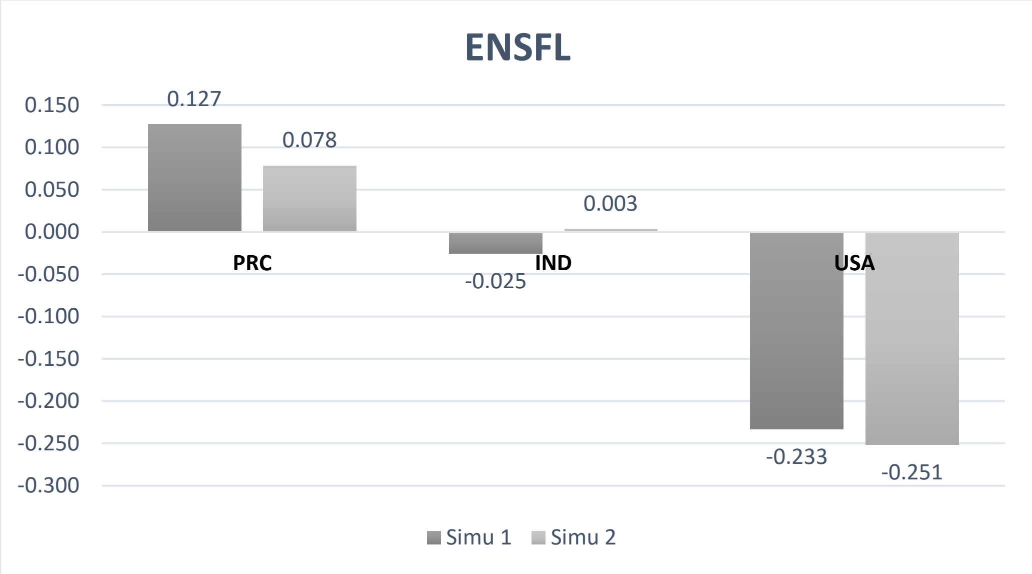
Table 5. Contribution of inter-country feedback loop to the national energy use

	Simulation 1			Simulation 2		
	ENS^{PRC}	ENS^{IND}	ENS^{USA*}	ENS^{PRC}	ENS^{IND*}	ENS^{USA}
$SO^{IND-PRC}$			0.024			
$SO^{IND-USA}$			12.702			
$SO^{PRC-IND}$			0.410			
$SO^{PRC-USA}$			86.864			
$FB^{USA-IND}$		-225.127				
$IFB^{USA-PRC-IND}$		-1.483				
$SO^{PRC-IND}$		326.610				
$FB^{USA-PRC}$	-90.820					
$IFB^{USA-IND-PRC}$	-0.328					
$SO^{IND-PRC}$	-8.852					
$SO^{USA-PRC}$					-10.754	
$SO^{USA-IND}$					-1838.995	
$SO^{PRC-USA}$					21.200	
$SO^{PRC-IND}$					1728.549	
$FB^{IND-USA}$						7.806
$IFB^{IND-PRC-USA}$						0.029
$SO^{PRC-USA}$						92.165
$FB^{IND-PRC}$				-21.775		
$IFB^{IND-USA-PRC}$				-0.712		
$SO^{USA-PRC}$				-77.512		
Total	-100	100	100	-100	-100	100

Source: Authors' Calculation

Based on the results of two simulation exercises, the study calculates the ratio of energy-saving feedback loop to the outsourced energy use for the three countries. Figure 7 illustrates this calculation and substantiates that the USA in both the situations of being as a free-rider or a non-free-rider saves aggregate energy use of the three countries by outsourcing its production to China and India. On the other hand, China found serving to save energy usage of the outsourced energy requirement of India and the USA in the two simulation exercises by 0.127 and 0.078 respectively. Here, India is found saving energy as a non-free-rider country, whereas fail to save energy from outsourcing as a free-rider. Therefore, this analysis portrays the comparative positions of these countries in terms of how far their aggregate emission is adjusted in the inter-country energy flows to govern the global volume of energy consumption to a substantial extent.

Figure 7. Ratio of energy-saving feedback loop to the outsourced energy use



Source: Authors' Illustration

5. Conclusion

Based on a three-country IRIO model, the analysis found a few important directions for achieving future climate goals by the major emitter economies. China is the top energy user globally for its exceedingly ambitious demand-driven factors. India is having a galloping growth of energy demand due to its expanding manufacturing sector, huge population and prolongation of development objectives. On the other hand, the study found the USA as the least-subscribed country to contribute to the common global objective of combatting heat-trapping carbon emissions. Therefore, the present study indicates a lack of climate leadership by these top three major emitter economies so far. The study brings about new insights on the aspects of inter-country energy flows among the major emitter countries and gives rise to exploring the dimensions of both energy saving and energy decaying roles of international spillover and feedback effects.

IEA recognized doubling the current rate of energy intensity improvement over the decade as a key measure to meet the Net-Zero emissions by 2050. The report published from the recently convened 7th Annual Global Conference on Energy Efficiency in June 2022 also mentioned that faster action to improve efficiency could cut the global energy use equivalent to the size of China's total energy demand. The present study also found reduced energy intensity as the major dampening force to compensate for the demand-driven increased energy consumption. Using SDA exercise, the study also analysed the roles of relative energy-intensity proportions of the various energy sources and energy-intensity compositions of various industries in the aggregate reduction of energy intensities of the non-energy and energy sectors of China, the USA and India. Based on these results, the study postulates unevenness in the compliance of major emission-generating economies in terms of their performance for deploying renewable energy generation capacity for saving fossil-fuel energy usage and cutting down the emissions for global well-being. The study found the maximum contribution of the renewable sources of energy from biofuels and waste and nuclear power in the reduction of energy intensity from non-renewable sources in the case of China. In the USA, the energy-intensity reduction due to increased nuclear power consumption was found significantly high. However, the potential of biofuels and waste to generate useful energy is found marginally explored in the case of the USA and largely unexplored in the case of India. The study provokes a far-reaching research agenda by incorporating a large number of high emitter trade partners in a single framework analysis for evaluating the benefits of renewable energy deploying activities of the emitter economies in terms of global energy savings and emission mitigation.

References

Aichele, R., Felbermyr, G., 2015. Kyoto and carbon leakage: an empirical analysis of the carbon content of bilateral trade. *The Review of Economics and Statistics*. 97 (1), 104–115.

Alcántara, V., Duarte, R., 2004. Comparison of energy intensities in European Union countries: results of a structural decomposition analysis. *Energy Policy*. 32 (2), 177–189.

Balsalobre-Lorente, D., Driha, O.M., Shahbaz, M., Sinha, A., 2020. The effects of tourism and globalization over environmental degradation in developed countries. *Environmental Science and Pollution Research*. 27, 7130–7144.

Banerjee, S., 2019. Addressing the drivers of carbon emissions embodied in Indian exports: an index decomposition analysis. *Foreign Trade Review*. 54(4), 300-333. Doi: https://doi.org/10.1177/0015732519874208

Banerjee, S., 2020. Carbon Emissions Embodied in India–United Kingdom Trade: A Case Study on North–South Debate. *Foreign Trade Review*. 55(2), 199-215. Doi: https://doi.org/10.1177/0015732519894149

Banerjee, S., 2021a. Carbon adjustment in a consumption-based emission inventory accounting: a CGE analysis and implications for a developing country. *Environmental Science and Pollution Research*. 28, 19984-20001. Doi: https://doi.org/10.1007/s11356-020-11771-3

Banerjee, S., 2021b. Addressing the carbon emissions embodied in India’s bilateral trade with two eminent Annex-II parties: with input–output and spatial decomposition analysis. *Environment Development and Sustainability*. 23, 5430–5464. Doi: https://doi.org/10.1007/s10668-020-00824-9

Banerjee, S., 2021c. Conjugation of border and domestic carbon adjustment and implications under production and consumption-based accounting of India's National Emission Inventory: A recursive dynamic CGE analysis. *Structural Change and Economic Dynamics*. 57, 68-86. Doi: https://doi.org/10.1016/j.strueco.2021.01.007

Banerjee, S., Khan, M.A., Husnain, M.I.U., 2021b. Searching appropriate system boundary for accounting India's emission inventory for the responsibility to reduce carbon emissions. *Journal of Environmental Management*. 295, 112907. Doi: https://doi.org/10.1016/j.jenvman.2021.112907

Banerjee, S., 2022. Emission-decoupling accounting framework of the Environmental Kuznets Curve (EKC) for India with structurally decomposed production and consumption based drivers. *Management of Environmental Quality*. Doi: https://doi.org/10.1108/MEQ-03-2022-0050

Brand-Korrea, L.I., Brockway, P.E., Copeland, C.L., Foxon, T.J., Owen, A., Taylor, P.G., 2017. Developing an Input-Output Based Method to Estimate a National-Level Energy Return on Investment (EROI). *Energies*, 10, 534. Doi: doi: 10.3390/en10040534

Brizga, J., Feng, K., Hubacek, K, 2014. Drivers of greenhouse gas emissions in the Baltic States: A structural decomposition analysis. *Ecological Economics*. 98, 22-28.

Butnar, I., Llop, M., 2011. Structural decomposition analysis and input–output subsystems: Changes in CO2 emissions of Spanish service sectors (2000–2005). *Ecological Economics*. 70, 2012–2019.

Cao, Y., Zhao, Y., Wang, H., Li, H., Wang, H., Liu, Y., Shi, Q., Zhang, Y., 2019. Driving forces of national and regional carbon intensity changes in China: Temporal and spatial multiplicative structural decomposition analysis. *Journal of Cleaner Production*. 213, 1380-1410.

Casler, S.D., Rose, A., 1998. Carbon Dioxide Emissions in the U.S. Economy: A Structural Decomposition Analysis. *Environmental and Resource Economics*. 11, 349–363. Doi: https://doi.org/10.1023/A:1008224101980

Chang, N., Lahr, M.L., 2016. Changes in China's production-source CO2 emissions: insights from structural decomposition analysis and linkage analysis. *Economic Systems Research*. DOI: 10.1080/09535314.2016.1172476

Chen, Z., Liu, Y., Zhang, Y., Zhong, Z., 2021. Inter-regional economic spillover and carbon productivity embodied in trade: empirical study from the Pan-Yangtze River Delta Region. *Environmental Science and Pollution Research*. 28, 7390–7403. Doi: https://doi.org/10.1007/s11356-020-10947-1

Chen, Z., Ni, W., Xia, L., Zhong, Z., 2019. Structural decomposition analysis of embodied carbon in trade in the middle reaches of the Yangtze River. *Environmental Science and Pollution Research*. 26, 816–832. Doi: https://doi.org/10.1007/s11356-018-3662-y

Dietzenbacher, E., Los, B., 1998. Structural Decomposition Techniques: Sense and Sensitivity. *Economic Systems Research*. 10, 307–323.

Dietzenbacher, E., Hoekstra, R., 2002. The RAS Structural Decomposition Approach. In Hewings, G.J.D., Sonis, M., Boyce, D. (Eds.). Trade, Networks and Hierarchies. Modeling Regional and Interregional Economies. Berlin: Springer, 179–199.

Ghosh, A., Banerjee, S., 2022. Exploring the Relevance of Crude Oil Prices and Installed Generation Capacity in Prognosticating the NIFTY Energy Index. *Millennial Asia*. Doi:10.1177/09763996221081196

Guan, D., Hubacek, K., Weber, C.L., Peters, G.P., Reiner, D.M., 2008. The drivers of Chinese CO2 emissions from 1980 to 2030. *Global Environmental Change*. 18 (4), 626–634.

Hoekstra, R., van den Bergh, J.C.J.M., 2003. Comparing structural and index decomposition analysis. *Energy Economics*. 25 (1), 39–64.

IEA, 2019. Global Energy & CO2 Status Report. IEA, Paris. Web: https://www.iea.org/reports/global-energy-co2-status-report-2019

IEA, 2017. Three countries are leading the renewable energy revolution. *World Economic Forum*. Web: https://www.weforum.org/agenda/2018/02/countries-behind-global-renewable-energy-growth/

IEA, 2021. Renewables 2021 – Executive Summary. IEA. Web: https://www.iea.org/reports/renewables-2021/executive-summary

Kagawa, S., Inamura, H., 2001. A structural decomposition of energy consumption based on a hybrid rectangular input–output framework: Japan's case. *Economic System Research*. 13(4), 339–363.

Lim, H.J., Yoo, S.H., Kwak, S.J., 2009. Industrial CO2 emissions from energy use in Korea: A structural decomposition analysis. *Energy Policy*. 37, 686-698.

Lindner, S., Guan, D., 2014. A hybrid-unit energy input-output model to evaluate embodied energy and life cycle emissions for China's economy. *Journal of Industrial Ecology*. 18 (2), 201 - 211.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions. 2nd Edition. Cambridge University Press. Cambridge.

Okushima, S., Tamura, M., 2007. Multiple calibration decomposition analysis: energy use and carbon dioxide emission in the Japanese economy, 1970–1995. *Energy Policy*. 35(10), 5156–5170.

Pruitichaiwiboon, P., Lee, C.K., Baek, C.Y., Lee, K.M., 2011. Development and Application of an Energy Input-Output Table for an Energy Demand and Supply Activities Analysis. *Environmental Engineering Research*. 16(1), 19-27.

Roy, S., Das, T., Chakraborty, D., 2002. A Study on the Indian Information Sector: An Experiment with Input-Output Techniques. *Economic Systems Research*. 14, 107–129.

Sesso, P.P., Amâncio-Vieira, S.F., Zapparoli, S.F., Filho, U.A.S., 2020. Structural decomposition of variations of carbon dioxide emissions for the United States, the European Union and BRIC. *Journal of Cleaner Production*. 252, 119761. https://doi.org/10.1016/j.jclepro.2019.119761.

Singh, R., Singh, S., 2020. Domestic Sources of India's Trade Policy Preferences in RCEP Negotiations. *Journal of World Trade*. 54(4), 503-530, Web: https://kluwerlawonline.com/journalarticle/Journal+of+World+Trade/54.4/TRAD2020023

Singh, S., Singh, R., 2022. Revisiting the Debate on Import-Led Substitution and Export-Led Industrialization: Where Is India Heading Under Self-Reliant India? *Journal of World Trade*. 56(1), 111-140. Web: https://kluwerlawonline.com/journalarticle/Journal+of+World+Trade/56.1/TRAD2022005

Su, B., Ang, B.W., 2012. Structural decomposition analysis applied to energy and emissions: Some methodological developments. *Energy Economics*. 34, 177-188.

Su, B., Ang, B.W., Li, Y., 2017. Input-output and structural decomposition analysis of Singapore's carbon emissions. *Energy policy*. 106, 484-492.

Su, B., & Ang, B.W., 2017. Multiplicative structural decomposition analysis of aggregate embodied energy and emission intensities. *Energy Economics*. 65, 137-147.

Shepard, J.U., Pratson, L.F., 2020. Hybrid input-output analysis of embodied energy security. *Applied Energy*. 279, 115806.

Tandon, A., Ahmed, S., 2016. Technological change and energy consumption in India: a decomposition analysis. *Innovation and Development*. 6(1), 141-159, DOI: 10.1080/2157930X.2015.1114565

Wang, Q., Liu, Y., 2020. India's renewable energy: New insights from multi-regional input output and structural decomposition analysis. *Journal of Cleaner Production*. 283, 124230.

Wang, H., Ang, B.W., Su, B., 2017. A Multi-region Structural Decomposition Analysis of Global CO2 Emission Intensity. *Ecological Economics*. 142, 163-176.

Wang, S., Zhu, X., Song, D., Wen, Z., Chen, B., Feng, K., 2019. Drivers of CO2 emissions from power generation in China based on modified structural decomposition analysis. *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2019.02.199

Wei, J., Huang, K., Yang, S., Li, Y., Hu, T., Zhang, Y., 2017. Driving forces analysis of energy-related carbon dioxide (CO2) emissions in Beijing: an input output structural decomposition analysis. *Journal of Cleaner production*. 163, 58-68.

Wood, R., 2009. Structural decomposition analysis of Australia's greenhouse gas emissions. *Energy Policy*. 37 (11), 4943–4948.

Xu, Y., Dietzenbacher, E., 2014. A structural decomposition analysis of the emissions embodied in trade. *Ecological Economics*. 101, 10-20.

Yamakawa, A., Peters, G.P., 2011. Structural Decomposition Analysis of Greenhouse Gas Emissions in Norway 1990-2002. *Economic Systems Research*. 23(3), 303-318, DOI: 10.1080/09535314.2010.549461

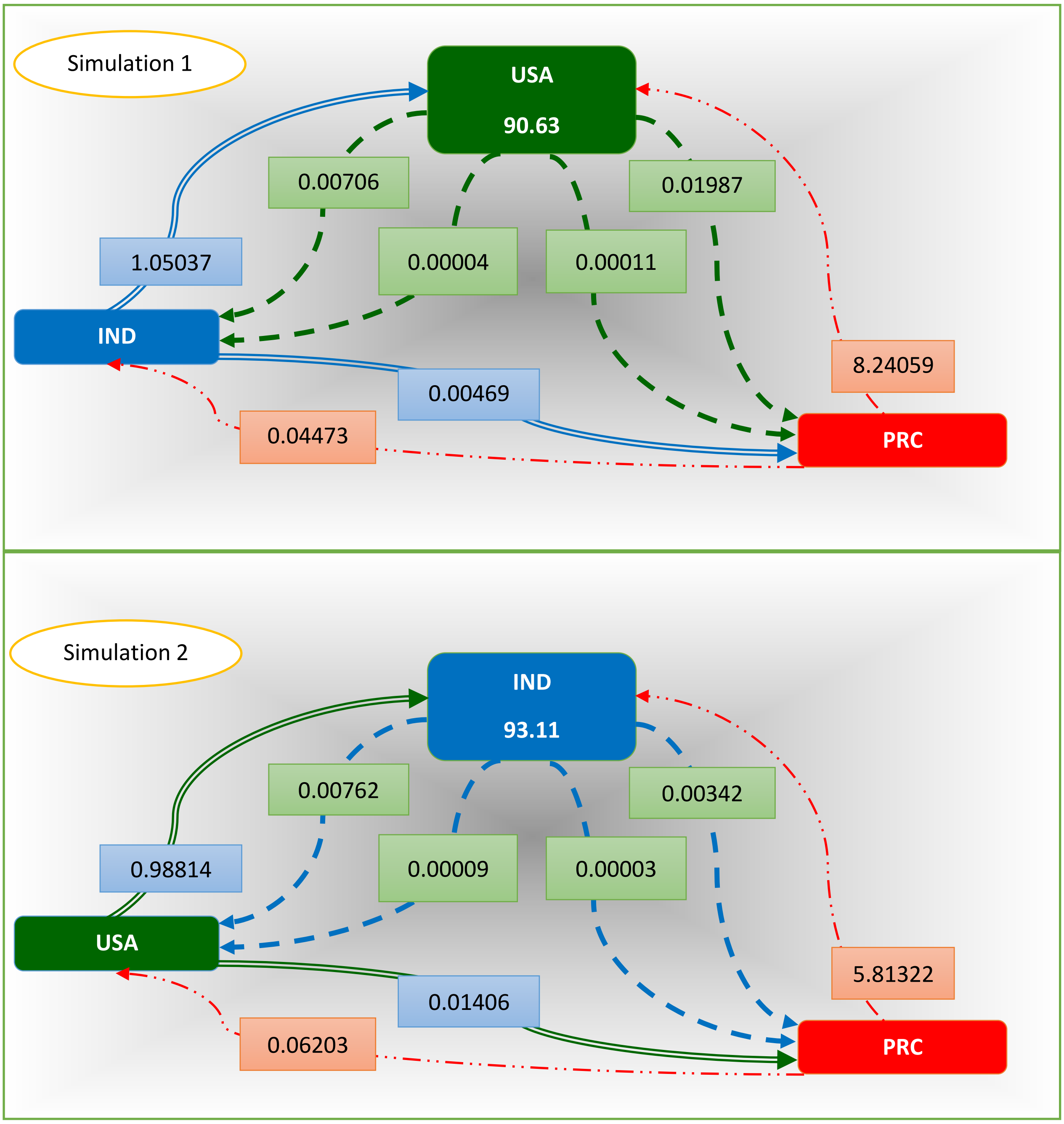
Yuan, R., Rodrigues, J.F.D., Behrens, P., 2019. Driving forces of household carbon emissions in China: A spatial decomposition analysis. *Journal of Cleaner Production*. 233, 932-945.

Zhang, Y., 2010. Supply-side structural effect on carbon emissions in China. *Energy Economics*. 32 (1), 186–193.

Zhu, B., Su, B., Li, Y., 2018. Input-output and structural decomposition analysis of India's carbon emissions and intensity, 2007/08 – 2013/14. *Applied Energy*. 1545-1556.

Appendix

Figure A.1. China-USA-India Energy Feedback Loop for Chemical, Metal and Machine Manufacturing (% of Energy Use)



Source: Authors' Illustration