

Supplementary Material C

Energy conservation conditions and CO₂ emission accounting in the hybrid input-output model

5 SC.1. Energy conservation conditions

The methodology explained in the main text is built on energy conservation conditions as follows. At first, the primary energy is extracted from the “ground” (also meaning any natural source like water) by primary energy sectors (Q_0) (**Fig. S1**). A part of the output is directly used by the non-energy sectors (Q_1)¹, while the rest goes to secondary energy sectors as inputs (Q_2). Therefore, the energy conservation condition concerning primary energy production is:

$$Q_0 = Q_1 + Q_2 \quad (C1)$$

In other words, total energy output from the primary sector is deemed equal to the energy extracted from the ground.

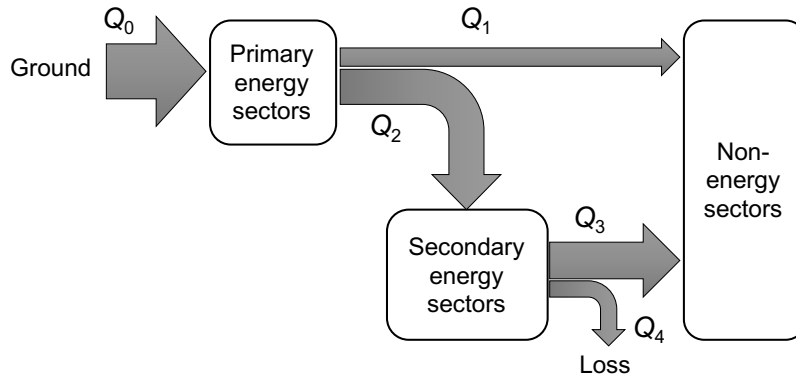


Fig. S1 Outline of energy flows from nature to economy.

Next, secondary energy sectors transform primary energy (and other secondary energy where necessary) into a form of secondary energy (Q_3). An example is the electricity sector, which uses various types of primary energy (e.g., natural gas and nuclear energy) as well as other secondary energy (e.g., heavy oil) as inputs to produce an electricity output. Because energy flows between secondary energy sectors cancel each other out, the net energy conservation condition concerning secondary energy production is:

$$Q_2 = Q_3 + Q_4 \quad (C2)$$

where: Q_4 is a loss during energy conversion within secondary energy sectors.

Alternatively, we may re-evaluate the amount of secondary energy output (Q_3) in terms of a “primary-energy equivalent” (Q_{3pe}) by multiplying Q_3 and a reciprocal of energy conversion efficiency:

¹ Miller and Blair (2009) neglected this flow for simplifying the explanation, but Japan’s energy balance tables contain direct primary-energy uses by non-energy sectors. We therefore expand their methodology to accommodate these flows in subsequent discussions.

$$Q_2 = Q_{3pe} = Q_3 \frac{Q_2}{Q_3} \quad (C3)$$

In other words, the primary energy equivalent is the amount of primary energy embodied in a secondary energy output. This is how I treated secondary energy outputs to derive the total energy requirement matrix α in the main text.

Finally, the primary and secondary energy outputs ($Q_1 + Q_3$) are consumed to produce non-energy commodities. Hence, from the viewpoint of non-energy sectors, the energy balance equation is:

$$Q_0 = Q_1 + Q_{3pe} = Q_1 + Q_3 \frac{Q_2}{Q_3} \quad (C4)$$

The equation implies that total primary energy input to commodity production (Q_0) is equal to the sum of direct primary energy inputs (Q_1) and the primary-energy equivalent of secondary energy inputs (Q_{3pe}).

It is noted that the above discussion (**Fig. S1**) omits another part of energy directly going to households as final demand (e.g., refilling a private car with gasoline). As discussed in **Supplementary Material B**, this demand is accounted for in exogenous final-demand sectors of the hybrid IO table. This treatment implies households' demand is regarded as an "external driver" initiating industrial chains of energy flows presented in **Fig. S1**. Since my hybrid IO model is solely purposed to describe such chains through backward-linkage effects, **Fig. S1** excludes final-demand sectors such as households.

SC.2. Energy flows in a simplified economy

To simplify discussions, I begin by adopting a simplified economy in which Sectors 1, 2 and 3 are respectively producing primary energy, secondary energy, and non-energy commodities. Flows of energy and commodities around a sector are shown in **Fig. S2**. I define x_j ($j = 1, 2, 3$) as an output of sector j ; g_{ii} ($i = 1, 2$) as primary energy input into an energy sector i ; z_{ij} as an input i ($i = 1, 2, 3$) necessary for driving a production process j ($j = 1, 2, 3$); and α_{ki} as a total energy requirement of type k ($k = 1, 2$) for producing i ($i = 1, 2, 3$).

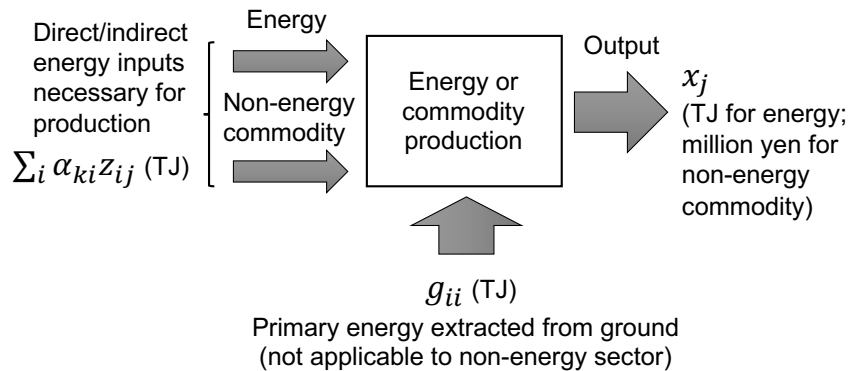


Fig. S2 Schematic flows of energy and commodities around a sector.
Source: Adopted from Bullard and Herendeen (1975) with modifications

The mission of energy sectors is to acquire energy from the ground (nature), process and deliver it in some form to the economy (non-energy sectors). Therefore, in both primary and secondary energy sectors, the main energy flow comprises: “the energy to be processed” coming into the box from below (the ground) and “the processed energy” coming out on the right as output. For the primary energy sector, energy input g_{11} corresponds to Q_0 and output x_1 to $Q_1 + Q_2$. For the secondary energy sector, primary energy input g_{22} corresponds to Q_2 and output x_2 to Q_3 (or Q_{3pe} if expressed in a primary-energy equivalent term). This accounting method implies that the sum of primary and secondary energy outputs ($x_1 + x_2$) is double counting Q_2 , the flow from the primary to secondary energy sector.

In addition to the main energy flows explained above, all sectors require direct as well as indirect energy inputs (energy embodied in non-energy commodities) necessary for driving the production processes. All these flows are due to economic transactions and come from the left of the box in **Fig. S2**. If a secondary energy sector requires other secondary energy inputs, it also comes from the left. These flows can be summarized as $\sum_i \alpha_{ki} z_{ij}$. For the non-energy sector, all direct/indirect energy necessary for production comes from economic transactions, i.e., from the left of the box in **Fig. S2**.

SC.3. Energy flows in the hybrid IO model

I reproduce here Eqs. (3) and (4) in the main text describing the energy flows among sectors in a matrix form:

$$\alpha \hat{x} = \alpha Z + G \quad (3)$$

$$\alpha = G(\hat{x})^{-1} L \quad (4)$$

where $\alpha = [\alpha_{ki}]$ is a matrix indicating the total energy requirement of type k in producing a unit output of sector i ($m \times n$); $\hat{x}$ is a diagonal matrix of the total outputs ($n \times n$); Z is a matrix of intermediate inputs ($n \times n$); G is a matrix of the primary energy inputs ($m \times n$), whose diagonal elements g_{ii} ($i = 1$ to m) are the primary energy input into the i th energy sector, with the other elements being zeros; L is the Leontief inverse matrix ($n \times n$), and m and n indicate the numbers of energy sectors (21) and all sectors (57), respectively.

The elements of $G(\hat{x})^{-1}$ in Eq. (4) are unity for primary energy sectors because $g_{11} = x_1$ by Eq. (C1), while those for secondary energy sectors are reciprocals of energy conversion efficiencies (Q_2/Q_3). This implies the total energy requirements with respect to secondary energy (Rows 8 to 21 in α) are expressed in primary-energy equivalent terms (see Eq. (C3)).

Therefore, for each secondary energy sector (Columns 8 to 21 in α), the sum of primary energy requirements (Q_2) must equal the sum of secondary energy requirements expressed in a primary-energy equivalent (Q_{3pe}) by Eq. (C3), because every secondary energy is ultimately derived from primary energy. Hence, I have an energy conservation condition for the secondary energy sectors:

$$\sum_{i=1}^7 (\alpha_{ij}) = \sum_{i=8}^{21} (\alpha_{ij}) \quad (j = 8 \text{ to } 21) \quad (C5)$$

Meanwhile, for the primary energy sectors ($j = 1$ to 7), the left-hand side of Eq. (C5) is always greater than the right-hand side by unity, which implies primary energy is extracted from the ground, that is, outside the economy (Miller and Blair 2009).

As for the non-energy sector, the left-hand side of Eq. (C5) expresses $Q_1 + Q_2$, while the right-hand side indicates $Q_{3pe} = Q_2$, so the equation does not hold. I therefore modify Eq. (C4) to obtain:

$$Q_0 - Q_1 = Q_{3pe} \quad (C6)$$

To acquire Q_1 , I construct a variant of the input coefficient matrix, $\tilde{A}$ ($n \times n$), which has identical elements with A , except for the zeros in the sub-matrices corresponding to rows and columns of secondary energy sectors (**Fig. S3a**). Using $\tilde{A}$, I can evaluate $\tilde{\alpha}$ as usual by Eq. (4), which consequently contains only direct energy flows from primary energy sectors to the non-energy sectors, Q_1 , in the absence of secondary energy sectors. I now arrive at an energy conservation condition concerning the non-energy sectors in accordance with Eq. (C6):

$$\sum_{i=1}^7(\alpha_{ij}) - \sum_{i=1}^7(\tilde{\alpha}_{ij}) = \sum_{i=8}^{21}(\alpha_{ij}) \quad (j = 22 \text{ to } 57) \quad (C7)$$

Using the hybrid IO tables compiled in **Supplementary Material A**, I derived α and $\tilde{\alpha}$, and confirmed the energy conservation conditions of Eqs. (C5) and (C7) with rounding errors of less than 0.1%, and hence the validity of the theory.

(a) $\tilde{A}$ ($n \times n$)

			Primary energy		Secondary energy		Non-energy
			Fossil	Non-fossil	Fossil	Non-fossil	
Sector No.			1-3	4-7	8-18	19-21	22-57
Primary energy	Fossil	1-3					
	Non-fossil	4-7					
Secondary energy	Fossil	8-18					
	Non-fossil	19-21					
Non-energy		22-57					

(b) $\bar{A}$ ($m \times n$)

			Primary energy		Secondary energy		Non-energy
			Fossil	Non-fossil	Fossil	Non-fossil	
Sector No.			1-3	4-7	8-18	19-21	22-57
Primary energy	Fossil	1-3					
	Non-fossil	4-7					
Secondary energy	Fossil	8-18					
	Non-fossil	19-21					

Fig. S3 Schematic diagram of the variants of the input coefficient matrix. *Note:* Elements in the shaded boxes are substituted by zero, while the rest are identical with the original input coefficient matrix A .

SC.4. CO₂ emission accounting of the hybrid IO model

This study confined analyses to CO₂ emissions due to the combustion of fossil fuels. Because CO₂ is emitted upon combustion, we need to be careful not to double count emissions as fossil fuels change hands from primary to secondary energy and to the non-energy sectors. Hence, unlike the energy model discussed above, here I do not allow any double counting among sectors. Solid arrows in **Fig. S4** indicate transactions where fossil fuels are combusted, and CO₂ emissions counted. Hence, it is necessary to avoid counting emissions in dashed transactions marked (1) to (3), as well as those within secondary fossil-fuel sectors, as follows.

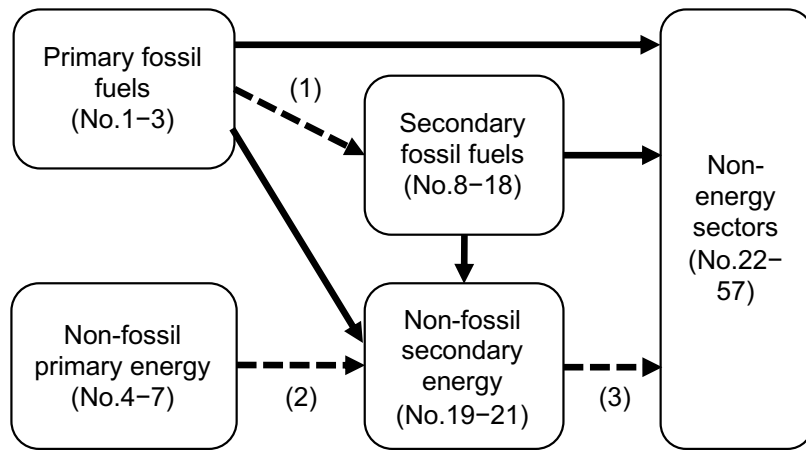


Fig. S4 Schematic of energy flows around sectors in view of CO₂ emissions. *Note:* Solid arrows indicate flows where CO₂ is emitted, while dashed ones where no CO₂ emission occurs.

First, I introduced the CO₂ emission coefficient c_i , which indicates the CO₂ emission when one unit of type- i energy is combusted (in t-CO₂/TJ). To exclude transactions (2) and (3) in **Fig. S4**, therefore, I set the CO₂ emission coefficients of non-fossil primary energy (Sectors 4–7) as well as non-fossil secondary energy (i.e., electricity, inhouse power and heat) (Sectors 19–21) to zero². Otherwise, emission coefficients for primary/secondary fossil fuels were obtained from ANRE (2021). Next, to exclude transactions (1) and within the secondary fossil-fuel sectors, I constructed another variant of the input coefficient matrix ($m \times n$), $\bar{A}$, which comprises rows of energy sectors and columns of all sectors. $\bar{A}$ has elements identical with A , except for the zeros in sub-matrices corresponding to transactions from primary/secondary fossil-fuel sectors to secondary fossil-fuel sectors (**Fig. S3b**).

Second³, I evaluated CO₂ emissions resulting from the direct uses of fossil fuel type i in producing a unit product of sector j by:

$$E^d = \hat{c}\bar{A} \quad (8)$$

² A part of renewables (biomass) and recoveries of wasted energy (mostly power generation with solid waste incineration) do emit CO₂, but I did not count them because they are partly carbon neutral and are out of the scope of this study.

³ The following part of discussions is reproduced from the main text (Section 2.4). Hence, Eqs. (8) to (10) refer to the equation numbers in the main text.

where E^d is the matrix of direct unit CO₂ emissions ($m \times n$); $\hat{c}$ is the diagonal matrix of CO₂ emission coefficients ($m \times m$); and $\bar{A}$ is the modified input coefficient matrix ($m \times n$).

- 5 Third, total CO₂ emissions from energy type i in producing a unit product of sector j , E^t , can be expressed by the sum of indirect emissions in producing inputs to sector j and the direct emission by sector j itself, as follows:

$$E^t = E^t A + E^d \quad (9)$$

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where E^t is a matrix of total unit CO₂ emissions ($m \times n$).

Finally, Eq. (9) can be modified to evaluate total unit CO₂ emissions as:

$$\begin{aligned} E^t(I - A) &= E^d \\ E^t &= E^d(I - A)^{-1} = E^d L \end{aligned} \quad (10)$$

Reference

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