Supporting Information

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Characterization of Economic Requirements for a "Carbon-Debt-Free Country"

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Methods and data

Production-based and consumption-based GHG emissions

Production-based emissions refers to the method of counting all the GHGs emitted in the course of commodity production as belonging to the country in which the production occurred. In other words, Japan's production-based emissions represent the GHGs emitted geographically within the country, which are equivalent to the amount that Japan reports to the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC).

In contrast, consumption-based emissions refers to the method of counting the GHGs emitted from commodity production as belonging to the country within which the commodity is ultimately consumed. In the case of Japan, then, the amount of domestic GHG emissions caused by the commodities that Japan ultimately consumes becomes the emission amount attributable to Japan. The GHG emissions from production of all the commodities destined for final consumption in Japan, even when that production occurs outside Japan, are thus counted as part of Japan's emissions.

Here, in both methods the direct emissions due to the fuel combustion associated with household use of automobiles, heating appliances, etc. are included in Japan's emissions.

Global link input-output (GLIO) model

Matrices and vectors of the Japanese case study

Table 1 in the main text represents the accounting framework for the Japanese case study using the GLIO model [1]. The matrices and vectors in the table are defined as follows.

Matrices

$\mathbf{X^I} = \left[X^{\mathrm{I}}_{i_1 j_1} \right]$: the volume of Japanese commodity i_1 used as an input for production of Japanese commodity j_1.

$\mathbf{X^{III}} = \left[X^{\mathrm{III}}_{i_1 q} \right]$: the output (export) of Japanese commodity i_1 to foreign region q.

$\mathbf{Y^{I(\mathit{k})}} = \left[Y^{\mathrm{I}(k)}_{p j_1} \right]$: the input volume (import) from foreign region p used in production of Japanese commodity i_1. The superscript k = (1... l) denotes the foreign commodity category.

$\mathbf{Y^{II(\mathit{k})}} = \left[Y^{\mathrm{II}(k)}_{p j_2} \right]$: the input volume (import) from foreign region p used in the hypothetical production of final-demand imported commodity j_2.

$\mathbf{Y}^{\mathbf{III}(k)} = \left[Y_{pq}^{\mathrm{III}(k)} \right]$: the transaction volume associated with foreign commodity *k* for foreign regions *p* and *q*. The diagonal component $Y_{p,q=p}^{\mathrm{III}(k)}$ of $\mathbf{Y}^{\mathbf{III}(k)}$ denotes the total intermediate input volume associated with domestic commodities in the foreign region.

Vectors

$\mathbf{f}^{JD} = \left[f_{i_1}^{JD} \right]$: the final domestic demand in Japan for Japanese commodity i_1.

$\mathbf{f}^{JI} = \left[f_{i_2}^{JI} \right]$: the final domestic demand in Japan for imported commodity i_2.

$\mathbf{f}^{G} = \left[f_{p}^{G} \right]$: the total final domestic demand in foreign region *p*.

$\mathbf{x}^{JD} = \left[x_{i_1}^{JD} \right]$: the total output of Japanese commodity i_1.

$\mathbf{x}^{JI} = \left[x_{i_2}^{JI} \right]$: the total volume supplied to Japan of final-demand imported commodity i_2. $\mathbf{x}^{G} = \left[x_{p}^{G} \right]$: the total output of foreign region *p*.

$\mathbf{v}^{JD} = \left[v_{j_1}^{JD} \right]$: the value added of Japanese commodity i_1.

$\mathbf{v}^{G} = \left[v_{q}^{G} \right]$: the values added of foreign region *q*.

Equilibrium of supply and demand of commodities

Turning now to the demand equilibrium of Japanese Commodities i_1 and i_2 and the demand equilibrium in Overseas Region *p*, expressing each in algebraic equations using the aforementioned matrices and vectors, yields the following equation (S1):

$$\begin{pmatrix} \mathbf{x}^{JD} \\ \mathbf{x}^{JI} \\ \mathbf{x}^{G} \end{pmatrix} = \begin{pmatrix} \mathbf{X}^{\mathrm{I}} & 0 & \mathbf{X}^{\mathrm{III}} \\ 0 & 0 & 0 \\ \sum_{k=1}^{l} \mathbf{Y}^{\mathrm{I}(k)} & \sum_{k=1}^{l} \mathbf{Y}^{\mathrm{II}(k)} & \sum_{k=1}^{l} \mathbf{Y}^{\mathrm{III}(k)} \end{pmatrix} \begin{pmatrix} \mathbf{i}^{JD} \\ \mathbf{i}^{JI} \\ \mathbf{i}^{G} \end{pmatrix} + \begin{pmatrix} \mathbf{f}^{JD} \\ \mathbf{f}^{JI} \\ \mathbf{f}^{G} \end{pmatrix} \qquad \text{(S1)}$$

In this equation, $\mathbf{i}^{JD}$ and $\mathbf{i}^{JI}$ represent n^{JD} and n^{JI}-dimensional column vectors, all of whose elements are unity; also, $\mathbf{i}^{G}$ is an n^{G}-dimensional column vector, all of whose elements are unity. The upper and middle equations in Eq. (S1) express the demand equilibrium equations for each commodity from Japan's domestic products and final demand imports. The lower equation is the demand equilibrium equation for each country in overseas regions trading domestic products.

Environmental extension of GLIO model

Global carbon footprint analysis

To apply the GLIO model to calculation of a nation's consumption-based GHG (greenhouse gas) emissions, or its global carbon footprint, we change the lower balance equation in Eq. (S1) as follows.

First, the export volumes $\mathbf{Y}^{\mathbf{I}(k)}$, $\mathbf{Y}^{\mathbf{II}(k)}$ and $\mathbf{Y}^{\mathbf{III}(k)}$ associated with overseas regions are converted to matrices $\tilde{\mathbf{Y}}^{\mathbf{I}(k)}$, $\tilde{\mathbf{Y}}^{\mathbf{II}(k)}$ and $\tilde{\mathbf{Y}}^{\mathbf{III}(k)}$ expressing the amount of embodied domestic GHG emissions attributable to the exporting country, including not only those due to the production (*process*) of Foreign Commodity *k* but also those associated with international transportation (*transport*) between Overseas Regions *p* and *q*, as shown in Eqs. (S2)–(S4). Similarly, the final demand $\mathbf{f}^{G}$ in the overseas regions is also expressed, based on Eq. (S5), as the amount of domestic GHG emissions $\tilde{\mathbf{f}}^{G}$ generated directly and indirectly by demand for the country's domestic commodities.

$$\tilde{\mathbf{Y}}^{\mathbf{I}(k)} = \sum_{k=1}^{l} (\overbrace{\hat{\boldsymbol{\omega}}^{(k)}\mathbf{Y}^{\mathbf{I}(k)}}^{\text{process}} + \overbrace{\hat{\boldsymbol{\sigma}}^{(k)}\mathbf{Y}^{\mathbf{I}(k)}}^{\text{transport}}) \tag{S2}$$

$$\tilde{\mathbf{Y}}^{\mathbf{II}(k)} = \sum_{k=1}^{l} (\overbrace{\hat{\boldsymbol{\omega}}^{(k)}\mathbf{Y}^{\mathbf{II}(k)}}^{\text{process}} + \overbrace{\hat{\boldsymbol{\sigma}}^{(k)}\mathbf{Y}^{\mathbf{II}(k)}}^{\text{transport}}) \tag{S3}$$

$$\tilde{\mathbf{Y}}^{\mathbf{III}(k)} = \sum_{k=1}^{l} (\overbrace{\hat{\boldsymbol{\omega}}^{(k)}(\mathbf{U} - \mathbf{I}) \otimes \mathbf{Y}^{\mathbf{III}(k)}}^{\text{process}} + \overbrace{\Theta^{(k)} \otimes (\mathbf{U} - \mathbf{I}) \otimes \mathbf{Y}^{\mathbf{III}(k)}}^{\text{transport}}) \tag{S4}$$

$$\tilde{\mathbf{f}}^{G} = \hat{\boldsymbol{\lambda}}^{G}\left(\mathbf{I} - \hat{\mathbf{m}}^{Gf}\right)\mathbf{f}^{G} \tag{S5}$$

In these equations, the symbol ^ denotes the diagonal matrix of the vector and $\boldsymbol{\omega}^{(k)} = \left[\omega_{p}^{(k)}\right]$ signifies the embodied domestic GHG emission intensity, representing the direct and indirect GHG emissions generated domestically in overseas region *p* per unit of export commodity *k*. For a country with an input–output table, $\boldsymbol{\omega}^{(k)}$ can be obtained by means of conventional environmental input–output analysis based on a domestic system boundary. In the case of a country lacking an input–output table, $\boldsymbol{\omega}^{(k)}$ needs to be estimated by making some kind of assumption. One possible approach would be to identify technological similarities between the country in question and a country that does have an input–output table, using the latter table as a surrogate for the country lacking a table. Given the conceptual similarity to the life cycle inventory data required for Life Cycle Assessment, such data could be also be used to estimate $\boldsymbol{\omega}^{(k)}$. Alternatively, the simplified method used in this paper can be applied.

Consequently, $\boldsymbol{\sigma}^{(k)} = \left[\sigma_p^{(k)}\right]$ corresponds to the amount of GHG generated in transporting one unit of commodity *k* exported from overseas region *p* to Japan. In addition, $\boldsymbol{\Theta}^{(k)} = \left[\Theta_{pq}^{(k)}\right]$ expresses the GHG emission incurred in the transportation of one unit of commodity *k* exported from overseas region *p* to overseas region *q*. At this point, $\mathbf{U} = \left[U_{pq} = 1\right]$ is a matrix all of whose elements are unity, with $\mathbf{I}$ indicating an n^G-dimensional unit matrix.

Furthermore, $\boldsymbol{\lambda}^G = \left[\lambda_p^G\right]$ refers to the direct and indirect GHG emission generated per unit of final domestic demand for domestic commodities in overseas region *p*, while $\mathbf{m}^{Gf} = \left[m_p^{Gf}\right]$ denotes the fraction of imports in the final demand of overseas region *p.* The operator $\otimes$ is the Hadamard product, i.e. element-wise multiplication. Eq. (S4) makes the embodied GHG emission of the diagonal element of $\mathbf{Y}^{\mathbf{III}(k)}$ that denotes the intermediate input of domestic commodities in overseas regions zero by multiplying $(\mathbf{U}-\mathbf{I})$ by $\mathbf{Y}^{\mathbf{III}(k)}$. In other words, the calculation method employed here characterizes all the GHG emissions in an overseas region as being attributable to the final demand for exports and domestic products in the region.

Subsequently, a material balance of GHG emissions in overseas regions is developed using the above matrices and vectors, as shown in Eq. (S6). In this equation $\tilde{\mathbf{x}}^G = \left[\tilde{x}_p^G\right]$ thus represents the total GHG burden arising in Overseas Region *p*.

$$\begin{pmatrix} \mathbf{x}^{JD} \\ \mathbf{x}^{JI} \\ \tilde{\mathbf{x}}^{G} \end{pmatrix} = \begin{pmatrix} \mathbf{X}^{\mathrm{I}} & 0 & \mathbf{X}^{\mathrm{III}} \\ 0 & 0 & 0 \\ \sum_{k=1}^{l} \tilde{\mathbf{Y}}^{\mathrm{I}(k)} & \sum_{k=1}^{l} \tilde{\mathbf{Y}}^{\mathrm{II}(k)} & \sum_{k=1}^{l} \tilde{\mathbf{Y}}^{\mathrm{III}(k)} \end{pmatrix} \begin{pmatrix} \mathbf{i}^{JD} \\ \mathbf{i}^{JI} \\ \mathbf{i}^{G} \end{pmatrix} + \begin{pmatrix} \mathbf{f}^{JD} \\ \mathbf{f}^{JI} \\ \tilde{\mathbf{f}}^{G} \end{pmatrix} \tag{S6}$$

Assuming that intermediate input and total output are directly proportional, regardless of whether one or both are converted to the embodied GHG emissions, the input coefficient matrices are established as follows;

$$\mathbf{A}_{11} = \mathbf{X}^{\mathbf{I}} (\hat{\mathbf{x}}^{JD})^{-1}, \tag{S7}$$

$$\widetilde{\mathbf{A}}_{13} = \mathbf{X}^{\mathbf{III}} (\hat{\tilde{\mathbf{x}}}^{G})^{-1}, \tag{S8}$$

$$\widetilde{\mathbf{A}}_{31}^{(k)} = \widetilde{\mathbf{Y}}^{\mathbf{I}(k)} (\hat{\mathbf{x}}^{JD})^{-1}, \tag{S9}$$

$$\widetilde{\mathbf{A}}_{32}^{(k)} = \widetilde{\mathbf{Y}}^{\mathbf{II}(k)} (\hat{\mathbf{x}}^{JI})^{-1}, \tag{S10}$$

$$\widetilde{\mathbf{A}}_{33}^{(k)} = \widetilde{\mathbf{Y}}^{\mathbf{III}(k)} (\hat{\tilde{\mathbf{x}}}^{G})^{-1}. \tag{S11}$$

These are substituted into Eq. (S6), which is then modified to yield Eq. (S12). Solving for $\begin{pmatrix} \mathbf{x}^{JD} & \mathbf{x}^{JI} & \tilde{\mathbf{x}}^{G} \end{pmatrix}^{trans}$, we can obtain Eq. (13), where matrix **I** represents the identity matrix of size (($n^{JD} + n^{JI} + n^{G}$) × ($n^{JD} + n^{JI} + n^{G}$)).

$$\begin{pmatrix} \mathbf{x}^{JD} \\ \mathbf{x}^{JI} \\ \tilde{\mathbf{x}}^{G} \end{pmatrix} = \begin{pmatrix} \mathbf{A}_{11} & 0 & \tilde{\mathbf{A}}_{13} \\ 0 & 0 & 0 \\ \sum_{k=1}^{l} \tilde{\mathbf{A}}_{31}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{32}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{33}^{(k)} \end{pmatrix} \begin{pmatrix} \mathbf{x}^{JD} \\ \mathbf{x}^{JI} \\ \tilde{\mathbf{x}}^{G} \end{pmatrix} + \begin{pmatrix} \mathbf{f}^{JD} \\ \mathbf{f}^{JI} \\ \tilde{\mathbf{f}}^{G} \end{pmatrix} \tag{S12}$$

$$\begin{pmatrix} \mathbf{x}^{JD} \\ \mathbf{x}^{JI} \\ \tilde{\mathbf{x}}^{G} \end{pmatrix} = \left\{ \mathbf{I} - \begin{pmatrix} \mathbf{A}_{11} & 0 & \tilde{\mathbf{A}}_{13} \\ 0 & 0 & 0 \\ \sum_{k=1}^{l} \tilde{\mathbf{A}}_{31}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{32}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{33}^{(k)} \end{pmatrix} \right\}^{-1} \begin{pmatrix} \mathbf{f}^{JD} \\ \mathbf{f}^{JI} \\ \tilde{\mathbf{f}}^{G} \end{pmatrix} \tag{S13}$$

Here, we focus solely on Japan's domestic final demands $\mathbf{f}^{JD}$ and $\mathbf{f}^{JI}$, and introduce the column vector $\mathbf{d}^{JD} = \left[d_{i_1}^{JD} \right]$, which has as its element the direct GHG emission $d_{i_1}^{JD}$ per unit production of Japanese commodity i_1. From Eq. (S14) it is possible to obtain four brock matrices $\mathbf{E}^{JD,JD} = \left[e_{i_1 j_1}^{JD,JD} \right]$, $\mathbf{E}^{JD,JI} = \left[e_{i_1 j_2}^{JD,JI} \right]$, $\mathbf{E}^{G,JD} = \left[e_{pj_1}^{G,JD} \right]$ and $\mathbf{E}^{G,JI} = \left[e_{pj_2}^{G,JI} \right]$. The element $e_{i_1 j_1}^{JD,JD}$ represents the GHG emissions in Japan from the production of commodity i_1 induced by $f_{i_1=j_1}^{JD}$, Japan's domestic final demands for commodity j_1. The element $e_{i_1 j_2}^{JD,JI}$ denotes the GHG emissions in Japan from the production of commodity i_1 induced by $f_{i_2=j_2}^{JI}$, Japan's domestic final demands for import commodity j_2. On the other hand, the elements $e_{pj_1}^{G,JD}$ and $e_{pj_2}^{G,JI}$ represent the GHG emissions in foreign country *p* induced by $f_{i_1=j_1}^{JD}$ and $f_{i_2=j_2}^{JI}$, respectively.

$$\begin{pmatrix} \mathbf{E}^{JD,JD} & \mathbf{E}^{JD,JI} & 0 \\ 0 & 0 & 0 \\ \mathbf{E}^{G,JD} & \mathbf{E}^{G,JI} & 0 \end{pmatrix} = \mathrm{diag}\begin{pmatrix} \mathbf{d}^{JD} \\ 0 \\ \mathbf{i}^{G} \end{pmatrix} \left\{ \mathbf{I} - \begin{pmatrix} \mathbf{A}_{11} & 0 & \tilde{\mathbf{A}}_{13} \\ 0 & 0 & 0 \\ \sum_{k=1}^{l} \tilde{\mathbf{A}}_{31}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{32}^{(k)} & \sum_{k=1}^{l} \tilde{\mathbf{A}}_{33}^{(k)} \end{pmatrix} \right\}^{-1} \mathrm{diag}\begin{pmatrix} \mathbf{f}^{JD} \\ \mathbf{f}^{JI} \\ 0 \end{pmatrix} \quad \text{(S14)}$$

in which diag means diagonalization of the vector.

Therefore, Q_{global}^{JP} of Eq. (1) in the main text is obtainable from Eq. (S15), determining C_{coms}^{JP} in Eq. (1).

$$Q_{global}^{JP} = \sum_{i_1=1}^{n^{JD}} \sum_{j_1=1}^{n^{JD}} e_{i_1 j_1}^{JD,JD} + \sum_{i_1=1}^{n^{JI}} \sum_{j_2=1}^{n^{JI}} e_{i_1 j_2}^{JD,JI} + \sum_{p=1}^{n^{G}} \sum_{j_1=1}^{n^{JD}} e_{pj_1}^{G,JD} + \sum_{p=1}^{n^{G}} \sum_{j_2=1}^{n^{JI}} e_{pj_2}^{G,JI} \quad \text{(S15)}$$

Economic and environmental data compilation

Japanese sectors

This study has analyzed the domestic and overseas GHG emissions associated with Japanese final demand. The following explains the methods used for calculating the data used in this analysis. As far as possible, the statistical data used were for the year

2005.

First, as shown in Eq. (S16), the intermediate input matrix $\mathbf{X}^{\mathbf{I}}$ related to domestic products was derived by deducting the import matrix $\mathbf{M} = \left[M_{i_1 j_i} \right]$ signifying the input of Import i_1, which competes against Domestic Product i_1, from matrix $\mathbf{X} = \left[X_{i_1 j_1} \right]$, which represents the intermediate input including Domestic Product i_1 and the competing Import i_1 into Domestic Product j_1.

$$\mathbf{X}^{\mathbf{I}} = \mathbf{X} - \mathbf{M} \qquad \text{(S16)}$$

The transaction volumes of $\mathbf{X}$, $\mathbf{M}$, $\mathbf{f}^{JD}$, $\mathbf{f}^{JI}$, $\mathbf{x}^{JD}$ and $\mathbf{x}^{JI}$ are denoted in monetary units (million yen) using the values in the Basic Transaction Table of the 2005 Input-Output Table of Japan (JIOT)[2].

The number of domestic sectors, n^{JD}, was set at 406, so that results would provide a detailed picture of household consumption. Although the JIOT defines coal, crude oil and natural gas production activities as a single "coal, crude oil and natural gas mining sector", the present study has additionally defined a "coal mining sector", a "crude oil mining sector" and a "natural gas mining sector", which are mutually independent because the countries from which these resources are imported differ.

These three sectors were assumed to have no mutual business transactions. On the other hand, output of coal, crude oil and natural gas, i.e. how much and to which sectors they are input, are respectively described in JIOT, and these data were used for the present study. Because of data restrictions on inputs to the three sectors, however, this study assumed that input to each of the three sectors is only from the "coal, crude oil and natural gas mining sector". That is, we estimated the input to each sector by allocating output of the "coal, crude oil and natural gas mining sector", based on each sector's domestic output.

For matrix $\mathbf{X}^{\mathbf{III}}$, although the total export volume $\mathbf{f}^{JD,EX} = \left[f_{i_1}^{JD,EX} \right]$ of Domestic

Product i_1 is listed in JIOT, it fails to identify the countries to which the product is exported and the export volumes concerned. Therefore, the export destinations were estimated through comparison with Japanese trade statistics (JTS) [3]. Although JTS list the export volume by destination (country and region) for each item in both monetary and physical units of the commodity, this study has used the former. Consistency between the items in JTS and Domestic Product i_1 in JIOT can be achieved using the "Trade Statistical Code Correspondence Table" included as a supplement to JIOT. On the basis of JTS thus gathered, the export volume, $EX_{i_1 q}$, of Domestic Product i_1 to Overseas Region *q* can be established. In contrast, $\sum_{q=1}^{n^G} EX_{i_1 q}$, which is the total value of export volumes in JTS on Domestic Product i_1, and $f_{i_1}^{JD,EX}$, as listed in JIOT, do not necessarily correspond in terms of their monetary value. For that reason, $\mathbf{S} = \left[S_{i_1 q} \right] = \left[EX_{i_1 q} / \sum_{q=1}^{n^G} EX_{i_1 q} \right]$, which is an export share matrix by commodity by country, was developed from $EX_{i_1 q}$ and multiplied by vector $\mathbf{f}^{JD,EX}$, as shown in Eq. (S17), to establish matrix $\mathbf{X}^{\mathbf{III}}$.

$$\mathbf{X}^{III} = \hat{\mathbf{f}}^{JD,EX} \mathbf{S} \qquad \text{(S17)}$$

Similarly to matrix $\mathbf{Y}^{\mathbf{I}(k)}$, the import volume (in monetary units) by country, $IM_{i_1 p}$, of Imported Product i_1 that competes against Domestic Product i_1 can be obtained with reference to JTS. In this way, just as in the earlier case of exports, an import share matrix by commodity by country, $\mathbf{R} = \left[R_{i_1 p} \right] = \left[IM_{i_1 p} / \sum_{p=1}^{n^G} IM_{i_1 p} \right]$, can be developed from $IM_{i_1 p}$. Because matrix $\mathbf{M}$ represents the import volume of Imported Product i_1 into Domestic Commodity Sector j_1, as Eq. (S18), extracting and multiplying it by the import share matrix, $\mathbf{R}$, results in conversion to $\mathbf{Y}^{\mathbf{I}(i_1)} = \left[Y_{p j_1}^{\mathrm{I}(i_1)} \right]$, the import volume of Imported Product i_1 by overseas region. In this calculation, elements of

$\mathbf{t}^{[i_1]} = \left[t_{j_1}^{[i_1]} \right]$ for which $j_1 = i_1$ are equal to unity. All others are row vectors whose elements are zero. The superscript "*trans*" denotes the transposition of a matrix or vector. By definition, therefore, $M_{i_1 j_1} = \sum_{p=1}^{n^G} Y_{pj_1}^{\mathrm{I}(i_1)}$. Some service-related commodities have their import volumes listed in JIOT, but not in JTS. In this paper, imports of such commodities are imported from a hypothetical country where domestic commodities are produced with the same technology as Japan. This study has defined $\mathbf{Y}^{\mathbf{I}(k)}$, as in Eq. (S19), by aggregating $\mathbf{Y}^{\mathbf{I}(i_1)}$ in line with Commodity Category *k*, for which economic and GHG emission data can be collected.

The same approach was used for Final Demand Import i_2 according to Eqs. (S20) and (S21), for which purpose $\mathbf{Y}^{\mathbf{II}(k)}$ was determined by multiplying matrix $\mathbf{R}$ by the diagonal matrix of $\mathbf{f}^{JI}$ signifying the import volume and then aggregating the results. Furthermore, elements of $\mathbf{t}^{[i_2]} = \left[t_{j_2}^{[i_2]} \right]$ for which $j_2 = i_2$ are equal to unity; all others are row vectors whose elements are zero.

$$\mathbf{Y}^{\mathbf{I}(i_1)} = \mathbf{R}^{trans}\hat{\mathbf{t}}^{[i_1]}\mathbf{M} \tag{S18}$$

$$\mathbf{Y}^{\mathbf{I}(k)} = \sum_{i_1 \in k} \mathbf{Y}^{\mathbf{I}(i_1)} \tag{S19}$$

$$\mathbf{Y}^{\mathbf{II}(i_2)} = \mathbf{R}^{trans}\hat{\mathbf{t}}^{[i_2]}\hat{\mathbf{f}}^{JI} \tag{S20}$$

$$\mathbf{Y}^{\mathbf{II}(k)} = \sum_{i_2 \in k} \mathbf{Y}^{\mathrm{II}(i_2)} \tag{S21}$$

Direct GHG emissions per unit of production in each sector were taken from 3EID[4] and substituted into vector $\mathbf{d}^{JD}$.

Economic data on overseas sectors

The non-diagonal elements of the matrix $\mathbf{Y}^{\mathbf{III}(k)}$ represent the trade volumes of Foreign Commodity *k* among regions other than Japan, which in this study were estimated based on BACI (Base pour l'Analyse du Commerce International) [5], which improves the United Nations Commodity Trade Statistics Database (UN Comtrade) [6] for goods and the United Nations Service Trade Statistics Database [7] for services.

The diagonal element of $\mathbf{Y}^{\mathbf{III}(k)}$, $Y_{pp}^{\mathrm{III}(k)}$, on the other hand, can be acquired from each input-output table of Overseas Region *p* if such a table has indeed been prepared. Not that many countries have such tables, however, and in many of them one would have great difficulty obtaining the total value of intermediate inputs in any direct manner. Considering data availability, therefore, we performed an indirect estimate for such countries using the following method. For an input-output table, because of the nature of social accounting matrices, the total value of intermediate input for domestic products related to all Commodities *k*, which is $\sum_{k=1}^{l} Y_{p,q=p}^{\mathrm{III}(k)}$, equals the result of subtracting the value of final demand and total exports from the domestic output and adding the import value in the final demand. Consequently, if the values are unavailable from an input-output table for a particular country, the following values are applicable to determine the domestic output $\overline{x}_p^G$ and domestic final demand f_p^{GD} for total exports $exp_p^{total} = \sum_{k=1}^{l}\left(\sum_{j_1=1}^{n^{JD}} Y_{pj_1}^{\mathrm{I}(k)} + \sum_{j_2=1}^{n^{JI}} Y_{pj_2}^{\mathrm{II}(k)} + \sum_{q=1,q\neq p}^{n^G} Y_{pq}^{\mathrm{III}(k)}\right)$ and the import value in the final demand, $f_p^{GI} = m_p^{Gf} f_p^G$, and estimate $\sum_{k=1}^{l} Y_{p,q=p}^{\mathrm{III}(k)}$, as shown in Eq. (S22).

$$\sum_{k=1}^{l} Y_{p,q=p}^{\mathrm{III}(k)} = \overline{x}_p^G - f_p^{GD} - exp_p^{total} + f_p^{GI} \quad \text{(S22)}$$

Nevertheless, to separate f_p^{GI} explicitly, the direct import volume in the final demand must be identified and extracted from the non-diagonal elements of $\mathbf{Y}^{\mathrm{III}(k)}$. Moreover, a direct import sector of final demand must be inferred separately for the overseas sectors, in similar detail to the structure of Japan's commodity sector used in this model. The BACI data provide only data on the sum of the imports in the intermediate demand in Overseas Region *p* and the imports in the final demand, however, preventing insight into the countries of origin and commodity composition of the imports going directly to the final demand. These and other limitations on data availability render the accurate separation of import volumes that are consistent with f_p^{GI} from $\mathbf{Y}^{\mathrm{III}(k)}$ impossible.

Consequently, the model included the direct imports of final demand in the overseas sectors in the imports of intermediate demand, that is, it assumed all the direct imports of final demand in the overseas region are converted to domestic products without any additional economic and environmental input. It is hereby inferred that production activities providing direct imports to final demand exist in the intermediate demand of overseas sectors. Furthermore, the final demand sector implicitly adopts the input structure in which direct imports are purchased through such activities. Therefore the domestic output used in the model x_p^G was changed from $\overline{x}_p^G$ of actual value in statistics to $x_p^G = \overline{x}_p^G + f_p^{GI}$.

Although $Y_{p,q=p}^{\mathrm{III}(k)}$ cannot be estimated for each Foreign Commodity *k* using the above estimation method, in a footprint analysis the diagonal elements of $\mathbf{Y}^{\mathrm{III}(k)}$ become zero, based on $(\mathbf{U}-\mathbf{I})$ in Eq. (S4), and in practice become unnecessary. For that reason, no problems arise in the model analysis.

The domestic output of each country must be input to the equation $x_p^G = \overline{x}_p^G + f_p^{GI}$ and the final domestic demand must be added to f_p^G. Except when such values are available in the input-output table of each country, this study has generally used the Common Database of the United Nations Statistics Division (UNCDB) [8] for preparing the estimate. The UNCDB encompasses the domestic output of approximately 100 countries and the GDP of approximately 200 countries, based on which the elements of $\mathbf{f}^G$ were estimated using the relation $f_p^G = GDP_p + imp_p^{total} - exp_p^{total}$. Appropriate estimation was performed using the correlation between total domestic output and GDP when the data of a country considered in this study were not available from UNCDB. The element imp_p^{total} indicates the total imports in Overseas Region *p*, which can be estimated from $imp_p^{total} = \sum_{i_1=1}^{n^{JD}} X_{i_1,q=p}^{\mathrm{III}} + \sum_{k=1}^{l} \sum_{p=1,p\neq q}^{n^G} Y_{p,q=p}^{\mathrm{III}(k)}$.

The elements m_p^{Gf} indicating the direct import rate in the final demand in Eq. (S5) were estimated using the input-output table in GTAP ver.7[9] in cases where Overseas Region *p* is defined there, but according to Eq. (S23) when data for m_p^{Gf} were difficult to estimated due to difficulty of data availability. By definition, m_p^G is the result of dividing total imports, imp_p^{total}, by total domestic demand. The latter is given by adding domestic output, $\bar{x}_p^G$, to total imports and subtracting total exports, exp_p^{total}.

$$m_p^{Gf} \triangleq m_p^G = \frac{imp_p^{total}}{\tilde{x}_p^G + imp_p^{total} - exp_p^{total}} \tag{S23}$$

<u>*GHG emission data on overseas sectors*</u>

Let us now turn to the method used for deriving the embodied GHG emission intensity, $\boldsymbol{\omega}^{(k)} = \left[\omega_p^{(k)}\right]$. For every non-competitive import type related to Commodity *k* in Overseas Region *p*, the embodied domestic GHG emission intensity, $\omega_p^{(k)}$, is calculated from Eq. (S24) by following the approach of conventional environmental input-output analysis, viz.:

$$\omega_p^{(k)} = \mathbf{r}^{(p)} \left\{\mathbf{I} - \left(\mathbf{I} - \mathbf{M}^{(p)}\right)\mathbf{A}^{(p)}\right\}^{-1} \mathbf{t}^{[k]} \tag{S24}$$

where the relation $\mathbf{A}^{(p)} = \left[a_{ij}^{(p)}\right]$ is the input coefficient matrix consisting of Sectors *i* and *j* in Overseas Region *p*. In addition, $\mathbf{M}^{(p)} = \left[m_{ij}^{(p)}\right]$ is the import coefficient matrix of Sector *i* in Overseas Region *p*, and $\mathbf{r}^{(p)} = \left[r_j^{(p)}\right]$ is the unit direct GHG emission vector of Sector *j*. Also, $\mathbf{t}^{[k]} = \left[t^{[i=k]} = 1; t^{[i\neq k]} = 0\right]$ is a column vector, in which only the elements in Sector *i* applicable to Foreign Commodity *k* to be examined are unity, with all others zero.

As shown in Eq. (S25), $\boldsymbol{\lambda}^G = \left[\lambda_p^G\right]$ can be obtained by replacing $\mathbf{t}^{[k]}$ in Eq. (S24) with the column vector, $\mathbf{f}^{GD(p)} = \left[f_{p,i}^{GD}\right]$, indicating the final demand for the domestic products in Sector *i*, and dividing the result by the total final demand f_p^G.

$$\lambda_p^G = \frac{\mathbf{r}^{(p)} \left\{\mathbf{I} - \left(\mathbf{I} - \mathbf{M}^{(p)}\right)\mathbf{A}^{(p)}\right\}^{-1} \mathbf{f}^{GD(p)}}{\left(1 - m_p^{Gf}\right) f_p^G} \tag{S25}$$

However, if data on overseas regions lacking adequate input-output tables or unit direct GHG emission vector, $\mathbf{r}_p$, are not readily available, the inventory data developed for LCA might be used as a substitute, or an estimate made of the total GHG emission, D_p^{total}, and the GHG emission, D_p^{fd}, associated directly with final demand in Overseas Region *p*. Based on this, average $\overline{\varpi}_p^G$ and $\overline{\lambda}_p^G$ that do not depend on Foreign Commodity *k* or Sector *i* can be derived and applied.

$$\omega_p^{(k)} \triangleq \overline{\varpi}_p^G = \frac{D_p^{total} - D_p^{fd}}{f_p^G + exp_p^{total}} \tag{S26}$$

$$\lambda_p^{(k)} \triangleq \overline{\lambda}_p^G = \frac{D_p^{total} - D_p^{fd}}{f_p^G + exp_p^{total}} \tag{S27}$$

This study applied the GHG emissions of numerous countries in 2005, termed D_p^{total}, as published by the UNFCCC inventory [10], IEA data [11], Enerdata [12], EDGAR [13] ver. 4.1 and the Carbon Dioxide Information Analysis Center (CDIAC) [14]. For countries without available GHG emission data, the correlations with energy consumption data of various countries provided by IEA data and CDIAC, and GDP data in UNCDB were used to estimate the GHG emissions appropriately.

Results and discussion

Main economic contributors to consumption-based emissions

Government expenditure and fixed capital formation (public)

In Figure 2 in the main text, the domestic plus overseas emissions associated with government expenditure and fixed capital formation (public), together representing public expenditure, total 156 Mt CO_2eq (9.3%) and 101 Mt CO_2eq (6.1%), respectively. Of these, the overseas emissions, 39 Mt CO_2eq and 22 Mt CO_2eq, contribute only 2.2% (= 9.3–7.1) and 1.3% (= 6.1–4.8) to the segment's respective shares of 9.3% and 6.1%.

As Table S1 shows, in contrast to the case for household expenditure, with government expenditure foreign emissions are associated largely with a small number of specific commodities, with approximately 1.04% of these emissions deriving from expenditure on three medical services (JD363: 0.64%, JD362: 0.20% and JD361: 0.20%) representing government-subsidized health care and 0.74% from expenditure on public services, both central (JD346: 0.40%) and local (JD347: 0.34%). Together, these top 10 commodities account for 2.1%. The contribution of the other commodities is therefore very limited: just 0.1%.

In the case of public fixed capital formation, too, overseas emissions are dominated by expenditure on a small number of high-ranking commodities, with just 3 commodities contributing 0.84 of 1.3% (= 6.1–4.8): 0.38% deriving from publicly-funded road construction (JD286), 0.31% from publicly-funded waterworks on rivers, drainage systems, etc. (JD287) and 0.16% from non-wooden, non-residential construction (JD284). Among the reasons for the limited contribution of overseas emissions might be the fact that in this segment direct demand for imported goods is virtually non-existent compared with the above cases and that this public expenditure is aimed at stimulating domestic economic demand.

Fixed capital formation (private) and "Others"

Fixed capital formation (private) generates the second largest share of emissions: 319 Mt CO_2eq (19%), of which a substantial portion are overseas emissions: 130 Mt CO_2eq (8%). Of all the final demand segments, this is the one with the highest share of overseas emissions. In addition, "other" domestic final demand was found to induce 71 Mt CO_2eq (4.3%): 46 Mt CO_2eq in Japan (2.9%) and 24 Mt CO_2eq abroad (1.4%).

In the case of private fixed capital formation, the major contributors are "JD284: Non-residential construction (non-wooden)" (0.71%), "JD281: Residential construction (wooden)" (0.66%) and "JD282: Residential construction (non-wooden)" (0.66%). However, these construction-related domestic commodities are followed by demands for imported commodities, especially computer-related commodities (JI242: 0.39%, JI240: 0.32%, JI241: 0.27%). This means use of foreign-made computers in factories and offices induces non-negligible foreign emissions.

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Table S1: Top 10 commodities in five categories of Japanese final demand inducing foreign GHG emissions associated with consumption of commodities and their share (%) in Japanese consumption-based GHG emissions in 2005.

Rank	Consumption expenditure of households	Share (%)	Consumption expenditure of government	Share (%)	Gross domestic fixed capital formation (public)	Share (%)	Gross domestic fixed capital formation (private)	Share (%)	Other domestic final demand	Share (%)
1	JD138: Petroleum refinery products (inc. greases)	1.9	JD363: Medical service (medical corporations, etc.)	0.64	JD286: Public construction of roads	0.38	JD284: Non-residential construction (non-wooden)	0.71	JD391: General eating and drinking places (except coffee shops)	0.26
2	JD391: General eating and drinking places (except coffee shops)	0.8	JD346: Public administration (central) **	0.40	JD287: Public construction of rivers, drainages and others	0.31	JD282: Residential construction (non-wooden)	0.66	JD393: Eating and drinking places for pleasures	0.19
3	JD293: Electricity	0.68	JD347: Public administration (local) **	0.34	JD284: Non-residential construction (non-wooden)	0.16	JD281: Residential construction (wooden)	0.66	JD237: Cellular phones	0.12
4	JI85: Woven fabric apparel	0.67	JD362: Medical service (non-profit foundations, etc.)	0.20	JD292: Other civil engineering and construction	0.078	JI242: Electronic computing equipment (accessory equipment)	0.39	JD394: Hotels	0.11
5	JD303: Retail trade	0.60	JD361: Medical service (public)	0.20	JD288: Agricultural public construction	0.077	JI240: Personal Computers	0.32	JI394: Hotels	0.082
6	JI321: Air transport	0.57	JD348: School education (public) **	0.09	JD282: Residential construction (non-wooden)	0.038	JI241: Electronic computing equipment (except personal	0.27	JD369: Social welfare (private, non-profit) *	0.061
7	JI86: Knitted apparel	0.54	JD372: Nursing care (In-facility)	0.072	JI225: Applied electronic equipment	0.036	JD249: Passenger motor cars	0.25	JI37: Slaughtering and meat processing	0.031
8	JD302: Wholesale trade	0.40	JD354: Research institutes for natural science (pubic) **	0.068	JI241: Electronic computing equipment (except personal	0.029	JD302: Wholesale trade	0.21	JD392: Coffee shops	0.027
9	JD249: Passenger motor cars	0.35	JD371: Nursing care (In-home)	0.062	JI240: Personal Computers	0.021	JD292: Other civil engineering and construction	0.17	JD166: Hot rolled steel	0.026
10	JI394: Hotels	0.33	JD300: Waste management services (public) **	0.037	JD289: Railway construction	0.019	JI226: Electric measuring instruments	0.16	JD374: Private non-profit institutions serving households, n.e.c. *	0.025