Have consumption-based CO_2 emissions in developed countries peaked?

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Abstract: This study innovatively divided consumption-based CO_2 emissions of developed countries into domestic and foreign components using an environmentally extended multi-regional input–output model, and revealed their different driving factors using the structural decomposition analysis method. The results showed that the consumption-based emission peaked in 16 developed countries, and 14 countries peaked around 2008. Domestic emissions in all 16 developed countries have peaked, most of which accounted for 40-70% of the total consumption-based emissions. However, the foreign emissions driven by 9 peaking countries still kept increasing. Regarding domestic emissions, the decline of domestic carbon intensity was the main driving factor across 16 peaking countries. In terms of foreign emissions, carbon intensity decline, especially in main medium- and low-income countries, was the dominant factor in the CO_2 emissions decrease. Significant improvements in production technology levels of medium-income countries played a key role in weakening the carbon-increasing effects of foreign emissions during the post-peak period. Thus, to further promote global carbon emissions to peak as soon as possible, peaking developed countries should provide more emission reduction funds and technologies to support the decline of carbon intensity and the improvement of production technology in medium- and low-income countries.

Keywords: Developed countries; Consumption-based CO_2 emissions; Characteristic analysis; Structural decomposition analysis; Global climate governance

1. Introduction

With the rising threat of climate change, the Northern Hemisphere has suffered from rare extreme heat-wave events with higher temperatures and longer durations in 2022, substantially impacting economic growth and people's health (Witze, 2022). Anthropogenic greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2) emissions, are the primary driver of global warming (Davis and Caldeira, 2010; Davis et al., 2011; IPCC, 2021). To hold the increase in the global average temperatures to below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C, the Paris Agreement has identified the need for global CO_2 emissions to peak as soon as possible before undertaking rapid reductions (UNFCC, 2015).

Carbon emissions can be calculated by taking either production-based or consumption-based approaches (Peters, 2008; Davis and Caldeira, 2010). The production-based emission (PBE) encompasses all emissions in a country caused by domestic production processes, while the consumption-based emission (CBE) account for the emissions that are induced by the domestic consumption of a country, regardless of where the emissions occur. The difference between PBE and CBE of a country lies in the emissions embodied in trade. Conventionally PBE has been the most commonly used accounting measure in climate policymaking, while it has the potential to give misleading insights on climate change mitigation achievements due to the leakage phenomenon when the reduction emissions in developed countries occurs due to the transfer of their high-carbon industries to developing countries (Aichele and Felbermayr, 2012; Jakob and Marschinski, 2013; Huo et al., 2021). Notably, CBE well complements PBE since it better reflects the carbon emissions by tracking the emissions embodied in the global production chain caused by consumption (Peters, 2008; Peters et al., 2011). Hence, the CBE accounting method is necessary for achieving peak global CO_2 emissions and is more equitable for the processes of emissions reduction responsibility, international climate negotiations, and global climate governance (Fan et al., 2016; Wang and Zhou, 2018; Karakaya et al., 2019; Rocco et al., 2020).

Extensive studies have explored CBE, mostly focusing on individual countries (Baiocchi and Minx, 2010; Ninpanit et al., 2019; Wu et al., 2020; Kirikkaleli and Oyebanji, 2022) or comparing differences between PBE and CBE (Fan et al., 2016; Karakaya et al., 2019; Wu et al., 2020), which are essential to understand the emissions driven by consumption. Nevertheless, to the best of our knowledge, no studies among the studies mentioned above have explored the characteristics and causes of CO_2 emission peaks in developed countries from a consumption-based perspective. Hence, this study aims to explore the characteristics and driving factors of CO_2 emission peaking trends in developed countries from the perspective of consumption, which is a useful supplement to the existing literature. In addition, we consider that CBE in a given country is composed of domestic and foreign emissions (see Fig. 1), and these two parts in developed countries may show significant differences during the process of carbon emissions peaking, while no studies have yet involved these differences. Therefore, this study improves a new method of structural decomposition analysis (SDA) to address the above-mentioned shortcomings of the previous literature.

Compared with previous studies, the present study has some contributions in the following aspects: (1) This study is the first attempt to explore the characteristics and driving factors of the CO_2 emission peaking trend in developed countries from the perspective of consumption. It will help to understand the actual peaking situation of CO_2 emissions caused by the consumption of developed countries, and enrich the existing literature on consumption-based CO_2 emissions. (2) This study unveils a novel finding by decomposing CBE into domestic and foreign components—while the overall consumption-based CO_2 emissions of most developed countries have indeed peaked, the foreign emissions component, particularly in medium- and low-income countries, continues to rise, which offers fresh insights into global climate cooperation. (3) Through the driving factors analysis behind domestic and foreign emissions, with a special focus on the carbon emission impacts of changes in trade structures, this study also provides evidence for the importance of reducing carbon intensity and advancing production technology in medium- and low-income countries for achieving global carbon reductions.

The remainder of this paper is organized as follows: Section 2 conducts the literature review; Section 3 introduces the data and methodology; Section 4 discusses the trends and characteristics of 16 peaking developed countries, and explores the driving factors of domestic and foreign emissions changes at the pre-and post-peak; while Section 5 presents the main conclusions and relevant policy suggestions.

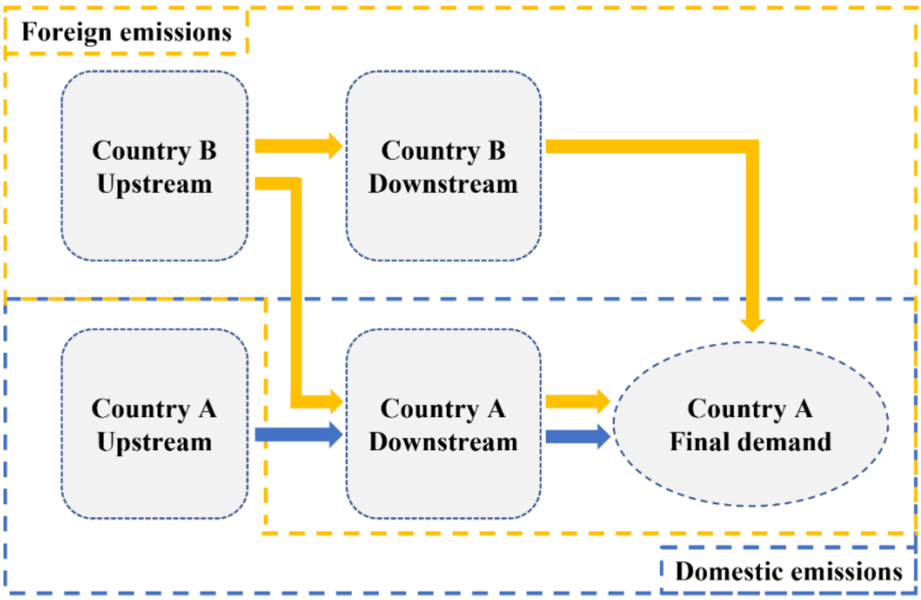

Fig. 1. Schematic diagram of the division of consumption-based emissions (CBE): For simplicity, the diagram assumes a system of two countries, A and B. The CO_2 emissions driven by consumption in country A have two parts: domestic emissions (i.e., those from country A) and foreign emissions (i.e., those from country B).

2. Literature Review

Peaking global CO_2 emissions is the prerequisite and primary task for achieving the climate goals of the Paris Agreement (Chou et al., 2022). The existing literature on carbon emission peak has mainly focused on the peaking trend, realization path, and cost-benefit analysis for developing countries. In particular, following the release of the Chinese government's CO_2 peaking pledge, an increasing number of studies have estimated China's emission trends, and attempted to testify the possibility of an emissions peak by 2030 (Liu et al., 2015; Fang et al., 2019; Wang et al., 2019). More ambitious studies have examined whether China could achieve an earlier peak of its CO_2 emissions (Mi et al., 2017a; Yu et al., 2018) and accordingly discussed the realization paths and measures, such as in terms of energy efficiency and transition (Guan et al., 2018; Gallagher et al., 2019; Zhang et al., 2023), CCS and sustainable development use (Liu et al., 2022; Chen et al., 2022), carbon emission trading systems (Wu and Zhu, 2021; Liu et al., 2022), and so on. For India, given the current rapid expansion of industrial production, population growth, and urbanization, it is widely recognized that the country will develop a rapidly growing trend of CO_2 emissions until 2050 (Pal and Mitra, 2017; Franco et al., 2017). Some studies have also suggested that in order to attain India's CO_2 emissions peak before 2040, more aggressive mitigation efforts and fundamental socio-economic revolutions must be taken in its various socio-economic fields (Mishra et al., 2015; Kumar and Madlener, 2016; Singh, 2018; Visjal et al., 2021). In addition, some scholars have also discussed the cost-benefit to reach CO_2 emissions peak. For example, Mi et al. (2017a) evaluated the socio-economic impact of China's emissions peak before 2030, and Huang et al. (2022) explored the impact of such a scenario on economic costs and health benefits.

Besides, the literature on the driving factors of carbon emissions has always been the spotlight of academic attention (Hoekstra and van den Bergh, 2003; Su and Ang, 2012), and structural decomposition analysis (SDA), the factor analysis technique commonly used to quantify the change of driving dependent variables over time, have become one of the preferred methods to study the driving factors behind environmental impacts (Lenzen, 2016; Wang et al., 2017). Through a critical review of the existing literature, we find that current studies on the driving factors of carbon emissions mainly focused on analyzing specific countries, including the US, the UK, Spain, Norway, Japan, Singapore, China, Brazil, and Thailand (Baiocchi and Minx, 2010; Butnar and Llop, 2011; Yamakawa and Peters, 2011; Lenzen et al., 2013; Feng et al., 2015; Cansino et al., 2016; Liang et al., 2016; Su et al., 2017; Ninpanit et al., 2019; Zheng et al., 2019; Su and Ang, 2020; Li et al., 2022; Ueda, 2022). In addition, a few studies have focused on the drivers of carbon emissions embodied in bilateral and multilateral trade, such as the trade of China–US, China–Australia, and US–German, as well as China's export trade (Zhao et al., 2016; Mi et al., 2017b; Huang et al., 2020; Wang and Han, 2021; Li and Ge, 2022). In terms of the factor decomposition of carbon emission changes, the above-mentioned literature mainly named the following as the main factors: carbon intensity, production structure, final consumption, per capita final consumption, and population.

The preceding review shows that the existing literature have conducted much work in estimating the future trend of CO_2 emissions, simulating the time and path of emissions peak, and discussing the cost-benefit to reach emissions peak, while most of them focused on developing countries. Although a few literatures have discussed the carbon peaking processes (Feng et al., 2015; Dong et al., 2019; Quere et al., 2019) and net zero-emissions paths (Greenblatt and Wei, 2016; Hultman et al., 2020; Schreyer et al., 2020; Rosa et al., 2021) in developed countries, all of which were based on the perspective of production. However, the production-based emissions peak of developed countries is due not only to decarbonization efforts in the energy sector but also emissions transfer through international trade as well (Peters et al., 2011; Wei et al., 2016; Huo et al., 2021), and these embodied emissions driven by the final consumption of developed countries may bring more CO_2 emissions on a global scale (Peters et al., 2011; Arto and Dietzenbacher, 2014; Wei et al., 2016). Based on this, the present study aims to fill the research gaps by analyzing the trend characteristics and driving factors of CO_2 emissions peak in developed countries from the perspective of consumption.

3. Data and Methodology

3.1 Data

Global input–output table, population, and CO_2 emissions data were obtained from Eora, a database developed by the Australian Research Council (ARC). The Eora database was selected here as it provides a complete set of global input–output tables with longer time series, and environmental satellite-based imagery accounts of homogeneous sector classifications, which are essential for analyzing the consumption-based peak time, and more accurately tracking developed countries' characteristics.

To facilitate presentation, this study combined 190 countries or regions into 42 (covering 10 countries in Asia, 12 in Africa, 14 in Europe, 2 in North America, 1 in South America and 1 in Oceania, see Table B1 for the specific country list) based on geographical location, economic development level, and carbon emissions trends, and the remaining 148 countries were combined into a whole, represented by "others" (Meng et al, 2018; Tian et al., 2022; Zheng et al., 2022). In addition, 26 sectors in the Eora database were also merged (see Table B2 for the specific sector list), and thus an EE-MRIO consisting of 42 countries and 16 sectors was established. Global input–output tables were also normalized from current year prices using a double deflationary approach (using 2002 as the base year), with deflators from the United Nations Statistics Division's National Accounts Main Aggregates Database.

3.2 Methodology

3.2.1 Environmentally extended multi-regional input–output model

The environmentally extended multi-regional input–output model (EE-MRIO) has been widely applied in consumption-based environmental accounting (Malik et al., 2019; Wei et al., 2022). Through the input–output relationship between different economic sectors across different regions, it can link upstream production with downstream consumption in a complex economic system to track all consumption-related CO_2 emissions to the original region of upstream emissions (Song et al., 2019; Zhang et al., 2020; Fan et al., 2022). Therefore, based on an environmentally extended multi-regional input–output analysis framework, this study calculated the consumption-based CO_2 emissions of different countries and conducted an SDA to explore the drivers of peak consumption-based emissions within developed countries. The structure of EE-MRIO, with m countries (or regions) and n sectors adopted in this study, is as follows (See Appendix A for detailed formula derivation):

$$\boldsymbol{E} = \widehat{\boldsymbol{Q}}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y}\,. \tag{1}$$

where consumption-based CO_2 emissions ($\boldsymbol{E}$) are related to carbon intensity diagonal matrix ($\widehat{\boldsymbol{Q}}$), Leontief inverse matrix $\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$, and final demand matrix ($\boldsymbol{Y}$). In Leontief inverse matrix $\boldsymbol{L}$, $\boldsymbol{I}$ is the identity matrix, and $\boldsymbol{A}$ is the multi-regional matrix of technical coefficients. The corresponding matrices are described as follows:

$$\widehat{\boldsymbol{Q}} = \begin{bmatrix} \widehat{\boldsymbol{Q}}^{1} & \cdots & \boldsymbol{0} & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \boldsymbol{0} & \cdots & \widehat{\boldsymbol{Q}}^{s} & \cdots & \boldsymbol{0} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \boldsymbol{0} & \cdots & \boldsymbol{0} & \cdots & \widehat{\boldsymbol{Q}}^{m} \end{bmatrix}, \text{ with } \widehat{\boldsymbol{Q}}^{s} = \begin{bmatrix} q_1^s & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ 0 & \cdots & q_j^s & \cdots & 0 \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & q_n^s \end{bmatrix},$$

q_j^s represents the carbon emissions per unit output of sector j in country s.

$$\boldsymbol{Y} = \begin{bmatrix} \boldsymbol{Y}^{11} & \cdots & \boldsymbol{Y}^{1s} & \cdots & \boldsymbol{Y}^{1m} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \boldsymbol{Y}^{r1} & \cdots & \boldsymbol{Y}^{rs} & \cdots & \boldsymbol{Y}^{rm} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \boldsymbol{Y}^{m1} & \cdots & \boldsymbol{Y}^{ms} & \cdots & \boldsymbol{Y}^{mm} \end{bmatrix}, \text{ with } \boldsymbol{Y}^{rs} = \begin{bmatrix} y_{11}^{rs} & \cdots & y_{1d}^{rs} & \cdots & y_{16}^{rs} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ y_{i1}^{rs} & \cdots & y_{id}^{rs} & \cdots & y_{i6}^{rs} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ y_{n1}^{rs} & \cdots & y_{nd}^{rs} & \cdots & y_{n6}^{rs} \end{bmatrix},$$

y_{id}^{rs} represents the d^{th} final demand in country s for the output of sector i in country r.

Considering that the consumption-based CO_2 emissions in a specific country s are composed of two parts: the emissions generated in country s to meet the final demands of country s (i.e., "domestic emissions"), and the emissions generated in country r to meet the final demands of country s (i.e., "foreign emissions"). To further understand peaking trends, and reasons of consumption-based CO_2 emissions in developed countries, this study decomposed the carbon emissions intensity diagonal matrix ($\widehat{\boldsymbol{Q}}$) into $\widehat{\boldsymbol{Q}}^{dom,s} = \begin{bmatrix} \mathbf{0} & \cdots & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \widehat{\mathbf{Q}}^{s} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \cdots & \mathbf{0} \end{bmatrix}$ containing carbon intensities only for country s (with zeros elsewhere), and $\widehat{\mathbf{Q}}^{fore,s} = \begin{bmatrix} \widehat{\mathbf{Q}}^{1} & \cdots & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \cdots & \widehat{\mathbf{Q}}^{m} \end{bmatrix}$ containing carbon intensities for all other countries, and zeros for country s; thus, the consumption-based CO_2 emissions for any country s were divided into domestic emissions ($\boldsymbol{E}^{dom,s}$) and foreign emissions ($\boldsymbol{E}^{fore,s}$), as shown in Eqs (2, 3):

$$\boldsymbol{E}^{dom,s} = \widehat{\boldsymbol{Q}}^{dom,s}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y}^{s}\ , \tag{2}$$

$$\boldsymbol{E}^{fore,s} = \widehat{\boldsymbol{Q}}^{fore,s}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y}^{s}\ . \tag{3}$$

3.2.2 Factor decomposition of domestic emissions

Structural decomposition analysis (SDA) allows dividing variables, such as output, income, or emissions, into different components, thereby assessing the driving effects of different factors (Araújo et al., 2020). Given that Eqs (2, 3) decompose the consumption-based CO_2 emissions of a specific country s into two parts: domestic emissions and foreign emissions, and the primary sources of consumption-based CO_2 emissions in each developed country have a different focus, this study used SDA to explore the impacts of different driving factors on the domestic and foreign components of consumption-based CO_2 emissions in developed countries. In addition, since the SDA method is non-unique, the two polar decomposition methods are widely used in academia (Arto and Dietzenbacher, 2014; Jiang and Guan, 2017); thus, this study adopted the two-polar decomposition methods for all subsequent analyses.

For the SDA of domestic emissions, final demand structure is an important factor affecting the domestic emissions of developed countries, this study referred to the practice of Liu et al. (2020) to decompose domestic emissions for a given country s into domestic emissions intensity ($\widehat{\boldsymbol{Q}}^{dom,s}$), production structure ($\boldsymbol{L}^s$), final demand commodity composition ($\boldsymbol{\psi}^s$), final demand category composition ($\boldsymbol{\delta}^s$), per capita final demand ($\boldsymbol{D}^s$), and population ($\boldsymbol{P}^s$), as shown in Eq. (4). Note that here $\widehat{\boldsymbol{Q}}^{dom,s}$, $\boldsymbol{L}^s$, $\boldsymbol{\psi}^s$, $\boldsymbol{\delta}^s$, $\boldsymbol{D}^s$, and $\boldsymbol{P}^s$ were expressed for a specific country s.

$$\boldsymbol{E}^{dom,s} = \widehat{\boldsymbol{Q}}^{dom,s} \underbrace{\boldsymbol{L}}_{\boldsymbol{L}=\sum_s \boldsymbol{L}^s} \underbrace{\boldsymbol{\psi}^s \boldsymbol{\delta}^s \boldsymbol{D}^s \boldsymbol{P}^s}_{\boldsymbol{Y}^s=\boldsymbol{\psi}^s \boldsymbol{\delta}^s \boldsymbol{D}^s \boldsymbol{P}^s} \qquad (4)$$

where $\widehat{\boldsymbol{Q}}^{dom,s}(mn \times mn)$ is the domestic carbon intensity matrix of country s; $\boldsymbol{L}^s(mn \times mn)$ is the Leontief inverse matrix of country s, representing the production structure in country s; $\boldsymbol{\psi}^s(mn \times md)$ is the final demand commodity composition matrix in country s, ψ_{id}^{rs} represents the ratio of the d^{th} final demand in country s to the final demand of sector i in country r, to the d^{th} total final demand in country s, $\psi_{id}^{rs} = \frac{y_{i,d}^{r,s}}{\sum_r \sum_i y_{i,d}^{r,s}}$; $\boldsymbol{\delta}^s(md \times md)$ is the final demand category composition matrix in country s, δ_d^s represents the ratio of the d^{th} final demand of country s to the total final demand of country s, $\delta_d^s = \frac{\sum_r \sum_i y_{i,d}^{r,s}}{\sum_d \sum_r \sum_i y_{i,d}^{r,s}}$; $\boldsymbol{D}^s(md \times md)$ is the per capita final demand matrix of country s, d^s represents the per capita final demand of country s, $d^s = \frac{\sum_d \sum_r \sum_i y_{i,d}^{r,s}}{p^s}$; $\boldsymbol{P}^s(md \times md)$ is the population matrix of country s, p^s

represents the total population of country s.

Accordingly, this study decomposed domestic emissions changes for a given country s by defining changes in domestic carbon intensity ($\Delta \boldsymbol{Q}^{dom,s}$), changes in production structure ($\Delta \boldsymbol{L}^{s}$), changes in final demand commodity composition ($\Delta \boldsymbol{\psi}^{s}$), changes in final demand category composition ($\Delta \boldsymbol{\delta}^{s}$), changes in per capita final demand ($\Delta \boldsymbol{D}^{s}$), and changes in population ($\Delta \boldsymbol{P}^{s}$), as shown in Eq. (5).

$$\Delta \boldsymbol{E}^{dom,s} = \Delta \boldsymbol{Q}^{dom,s} + \Delta \boldsymbol{L}^{s} + \Delta \boldsymbol{\psi}^{s} + \Delta \boldsymbol{\delta}^{s} + \Delta \boldsymbol{D}^{s} + \Delta \boldsymbol{P}^{s} \, . \qquad (5)$$

3.2.3 Factor decomposition of foreign emissions

For the SDA of foreign emissions, international trade is an important mechanism for monitoring foreign emissions of developed countries, particularly concerning the changes in the source and share of intermediate and final demands in developed countries having an important impact on foreign emissions. Therefore, according to different income levels, this study subdivided the source countries of intermediate and final demands in developed countries into four types: low-, medium-, high-income, and other countries (see Table B1 for the income classification criteria). Meanwhile, given that the changes in the carbon intensity of countries with different income levels will also affect the foreign emissions of developed countries, this study also divided the foreign carbon intensity of each country into the above four types. Finally, based on the decomposition of Xu and Dietzenbacher (2014), Arto and Dietzenbacher (2014), and Hoekstra et al. (2016), this study decomposed foreign emissions for a given country s into foreign carbon intensity ($\widehat{\boldsymbol{Q}}^{fore,s}$), total input structure ($\boldsymbol{A}^{*s}$), intermediate demand source structure ($\boldsymbol{C}^{s}$), final demand source structure ($\boldsymbol{F}^{s}$), final demand structure ($\boldsymbol{B}^{s}$), per capita final demand ($\boldsymbol{D}^{s}$), and population ($\boldsymbol{P}^{s}$), as shown in Eq. (6). Note that here $\widehat{\boldsymbol{Q}}^{fore,s}$, $\boldsymbol{A}^{*s}$, $\boldsymbol{C}^{s}$,

$\boldsymbol{F^s}$, $\boldsymbol{B^s}$, $\boldsymbol{D^s}$, and $\boldsymbol{P^s}$ were expressed for a specific country s.

$$\boldsymbol{E}^{fore,s} = \widehat{\boldsymbol{Q}}^{fore,s} \times \underbrace{\left[\boldsymbol{I} - \left(\sum_{s}\left(\boldsymbol{C}_{low}^{s} + \boldsymbol{C}_{med}^{s} + \boldsymbol{C}_{high}^{s} + \boldsymbol{C}_{others}^{s}\right)\right) \otimes \left(\sum_{s} \boldsymbol{A}^{*s}\right)\right]^{-1}}_{\boldsymbol{L}=(\boldsymbol{I}-\boldsymbol{A})^{-1}=(\boldsymbol{I}-\boldsymbol{C}\otimes\boldsymbol{A}^{*})^{-1}}$$
$$\times \underbrace{\left[\left(\left(\boldsymbol{F}_{low}^{s} + \boldsymbol{F}_{med}^{s} + \boldsymbol{F}_{high}^{s} + \boldsymbol{F}_{others}^{s}\right) \otimes (\boldsymbol{B}^{s})\right) \widehat{\boldsymbol{D}}^{s} \widehat{\boldsymbol{P}}^{s}\right]}_{\boldsymbol{Y}^{s}=\boldsymbol{F}^{s}\otimes\boldsymbol{Y}^{*,s}=(\boldsymbol{F}^{s}\otimes\boldsymbol{B}^{s})\boldsymbol{D}^{s}\boldsymbol{P}^{s}} \quad (6)$$

where $\widehat{\boldsymbol{Q}}^{fore,s}(mn \times mn)$ is the foreign carbon intensity matrix of country s. Based on different income levels, this study further divided the foreign carbon intensity of a specific country s into four types: low-, medium-, high-income, and other countries, represented by $\widehat{\boldsymbol{Q}}_{low}^{fore,s}$, $\widehat{\boldsymbol{Q}}_{med}^{fore,s}$, $\widehat{\boldsymbol{Q}}_{high}^{fore,s}$, and $\widehat{\boldsymbol{Q}}_{others}^{fore,s}$, respectively. Namely, $\widehat{\boldsymbol{Q}}^{fore,s} = \widehat{\boldsymbol{Q}}_{low}^{fore,s} + \widehat{\boldsymbol{Q}}_{med}^{fore,s} + \widehat{\boldsymbol{Q}}_{high}^{fore,s} + \widehat{\boldsymbol{Q}}_{others}^{fore,s}$. The decomposition diagram of $\widehat{\boldsymbol{Q}}^{fore,s}$ was shown in Fig. 2 (I). $\boldsymbol{C}^{s}(mn \times mn)$ is the intermediate sourcing share matrix in country s, and c_{ij}^{rs} represents the intermediate sourcing share provided by sector i in country r to sector j in country s. Similarly, according to different income levels, this study further divided the source countries of intermediate demand in a specific country s into low-, medium-, high-income, and other countries, represented by $\boldsymbol{C}_{low}^{s}$, $\boldsymbol{C}_{med}^{s}$, $\boldsymbol{C}_{high}^{s}$, and $\boldsymbol{C}_{others}^{s}$, respectively, where $\boldsymbol{C}^{s} = \boldsymbol{C}_{low}^{s} + \boldsymbol{C}_{med}^{s} + \boldsymbol{C}_{high}^{s} + \boldsymbol{C}_{others}^{s}$. The decomposition diagram of $\boldsymbol{C}^{s}$ is shown in Fig. 2 (II). $\boldsymbol{A}^{*s}(mn \times mn)$ is the total input structure matrix in country s, and A_{ij}^{*s} represents the technical coefficients of sector j in country s to sector i in all countries (irrespective of source country). $\boldsymbol{F}^{s}(mn \times mn)$ is the final demand share matrix in country s, and f_{i}^{rs} represents the final demand share provided by sector i in country r to country s. Similar to the $\boldsymbol{C}^{s}$-matrix above, this study further divided the source countries of country *s*' final demands into four types: low-, medium-, high-, and other countries, represented by $\boldsymbol{F}_{low}^{s}$, $\boldsymbol{F}_{med}^{s}$, $\boldsymbol{F}_{high}^{s}$, and $\boldsymbol{F}^s_{others}$, respectively, where $\boldsymbol{F}^s = \boldsymbol{F}^s_{low} + \boldsymbol{F}^s_{med} + \boldsymbol{F}^s_{high} + \boldsymbol{F}^s_{others}$. The decomposition diagram of $\boldsymbol{F}^s$ is shown in Fig. 2 (III). $\boldsymbol{B}^s(mn \times m)$ is the final demand structure matrix in country s, and b_i^s represents the share of sector i in the total final demand of country s(irrespective of the source country). $\widehat{\boldsymbol{D}}^s(m \times m)$ is the per capita final demand matrix of country s, and d^s represents the per capita final demand of country s. $\widehat{\boldsymbol{P}}^s(m \times m)$ is the population matrix of country s, and p^s represents the total population of country s. (See Appendix A for detailed formula derivation)

Therefore, the present study decomposed foreign emissions changes for a given country s by defining changes in foreign carbon intensity ($\Delta\boldsymbol{Q}^{fore,s}$), changes in intermediate demand source structure ($\Delta\boldsymbol{C}^s$), changes in total input structure ($\Delta\boldsymbol{A}^{*s}$), changes in final demand source structure ($\Delta\boldsymbol{F}^s$), changes in final demand structure ($\Delta\boldsymbol{B}^s$), changes in per capita final demand ($\Delta\boldsymbol{D}^s$), and changes in population ($\Delta\boldsymbol{P}^s$), as shown in Eq. (7):

$$\Delta\boldsymbol{E}^{fore,s} = \Delta\boldsymbol{Q}^{fore,s} + \Delta\boldsymbol{C}^s + \Delta\boldsymbol{A}^{*s} + \Delta\boldsymbol{F}^s + \Delta\boldsymbol{B}^s + \Delta\boldsymbol{D}^s + \Delta\boldsymbol{P}^s \,. \qquad (7)$$

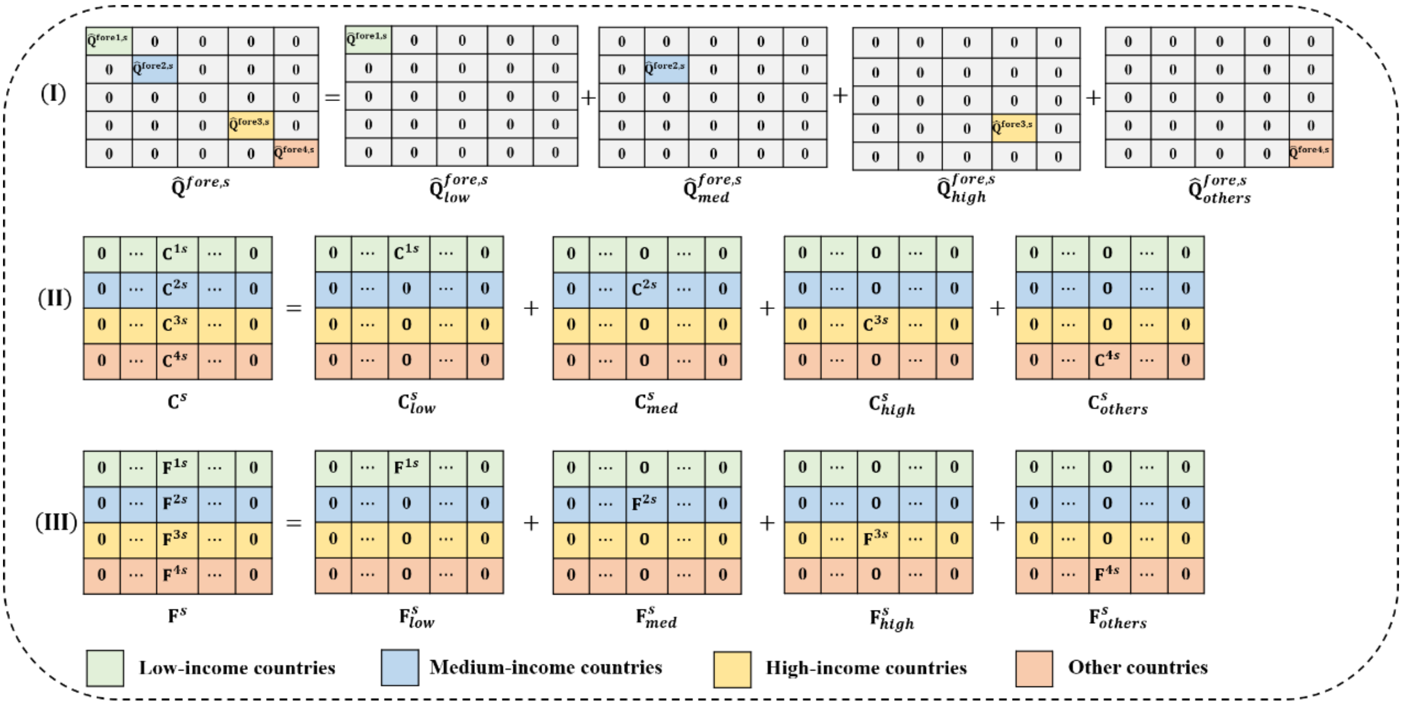

Fig. 2. Schematic diagram of the decomposition of $\widehat{\boldsymbol{Q}}^{fore,s}$, $\boldsymbol{C}^s$, and $\boldsymbol{F}^s$ matrices.

4. Results and Discussion

4.1 Characteristic analysis of consumption-based emissions trends in developed countries

16 developed countries achieved peaks in total and per capita consumption-based emissions during the study period. In terms of peak time, they were Germany (1991), Japan (1995), Denmark (1996), Finland (2003), France (2005), Italy (2005), Austria (2006), the UK (2006), Greece (2007), Iceland (2007), Spain (2007), Sweden (2007), the US (2007), the Netherlands (2008), Norway (2013), and Switzerland (2013). Among the 16 developed countries that reached peak consumption-based emissions, the peak years of most countries were concentrated in 2003–2008. The consumption-based emissions trends for each country are shown in Fig. B1.

From the perspective of total consumption-based emissions, the US, Japan, Germany were the peaking countries with highest consumption-based emissions respectively (with emissions of 7,446 Mt, 1,641 Mt and 1,147 Mt in 2016). The per capita consumption-based emissions are obviously higher (Fig. B2). In 2016, except for France, Italy, Greece, and Spain, the per capita consumption-based emissions in the rest 12 countries were higher than 10 $t \cdot person^{-1}$. The per capita consumption-based emissions of the US were continually > 20 $t \cdot person^{-1}$ during the study period, which was 2.81 times that of the medium-income country China, and 11.88 times that of India in 2016.

The final demand of developed countries drove both their own emissions, as well as a huge portion of the demand from other countries. The results showed that domestic emissions in 16 countries peaked, as shown in Fig. 3, but foreign emissions in some countries continued to rise or plateau. Specifically, foreign emissions in Norway and Switzerland continued to fluctuate and increase; whereas those of Denmark, the Netherlands, Spain, the US, Finland, France, and Germany are plateauing, and do not show any significant downward trends. Thus, for these developed countries, the peak of their consumption-based emissions is not "true" peaking, i.e., more emissions in other countries, which are not beneficial to the reductions of other countries.

Moreover, domestic and foreign emissions are very different in these countries (Fig. 3). Austria, Denmark, the Netherlands, Norway, Sweden, and Switzerland shared a trend in which the foreign emissions exceed the domestic. This emission trend indicated that the final demand of these countries drove the growth in domestic emissions before 1999; with more imports to meet their final demand the peaking process was accompanied by foreign emissions exceeding the domestic component, and after 2007, the final demand of these countries drove the growth of foreign emissions, resulting in large amounts of transferred CO_2 emissions. In the Netherlands, Sweden, and Switzerland, foreign emissions accounted for > 60% of total consumption-based emissions in 2016. Further dividing foreign emissions into representative low-, medium-, high-income, and other countries, the results showed that the proportion of emissions in low- and medium-income countries increased, but that of high-income country emissions declined, as shown in Fig. 4 (I). Specifically, the foreign emissions of these developed countries in medium- and low-income countries mainly come from China, especially the Netherlands (Fig. 4 (II)a, d).

Finland, France, Germany, the UK, and Iceland are characterized by "increasing foreign emissions approaching to decreasing domestic emissions". The share of foreign emissions in the UK, Germany, and Iceland in 2016 was near 50%, and foreign emissions in the UK and

Iceland even briefly exceeded domestic emissions in 2015. These countries also experienced an increase in the share of emissions from low- and medium-income countries, as well as a decline in the share of emissions from high-income countries over the study period (Fig. 4 (I)). Most countries already had > 20% of the emissions from medium-income countries, especially in the UK and Germany, medium-income countries have become their most important source of foreign emissions. During the study period, countries with the highest consumption-based emissions in Europe—Germany, the UK, and France—experienced a rapid increase in emissions from medium- and low-income countries, especially China (Fig. 4 (II)b, e). Taking 2016 as an example, CO_2 emissions of the above three countries from China were 95 Mt, 68 Mt, and 51 Mt, respectively, accounting for nearly 20% of their foreign emissions.

The remaining countries are characterized by domestic emissions greater than foreign emissions, which included Greece, Italy, Japan, Spain, and the US. In these countries, Taking US and Japan as examples, domestic emissions accounted for 79% and 69% of domestic emissions in 2016, respectively, far exceeding foreign emissions. Although the proportion of foreign emissions in the US and Japan is relatively low, their foreign emissions were large, and reached 1,558 Mt and 509 Mt, respectively. These countries showed an increase of more than 4% in the proportion of emissions from medium- and low-income countries (except for Japan), and a decline of more than 10% in the proportion of emissions from high-income countries during the study period. In particular, China, as a representative of typical medium-income countries is the largest source of foreign emissions for the US and Japan (accounting for 29% and 27% in 2016, respectively); meanwhile, emissions from low-income countries during the study period also experienced a rapid increase (Fig. 4 (II)c, f), increasing by 133 Mt and 42 Mt, respectively, compared to those in 1990.

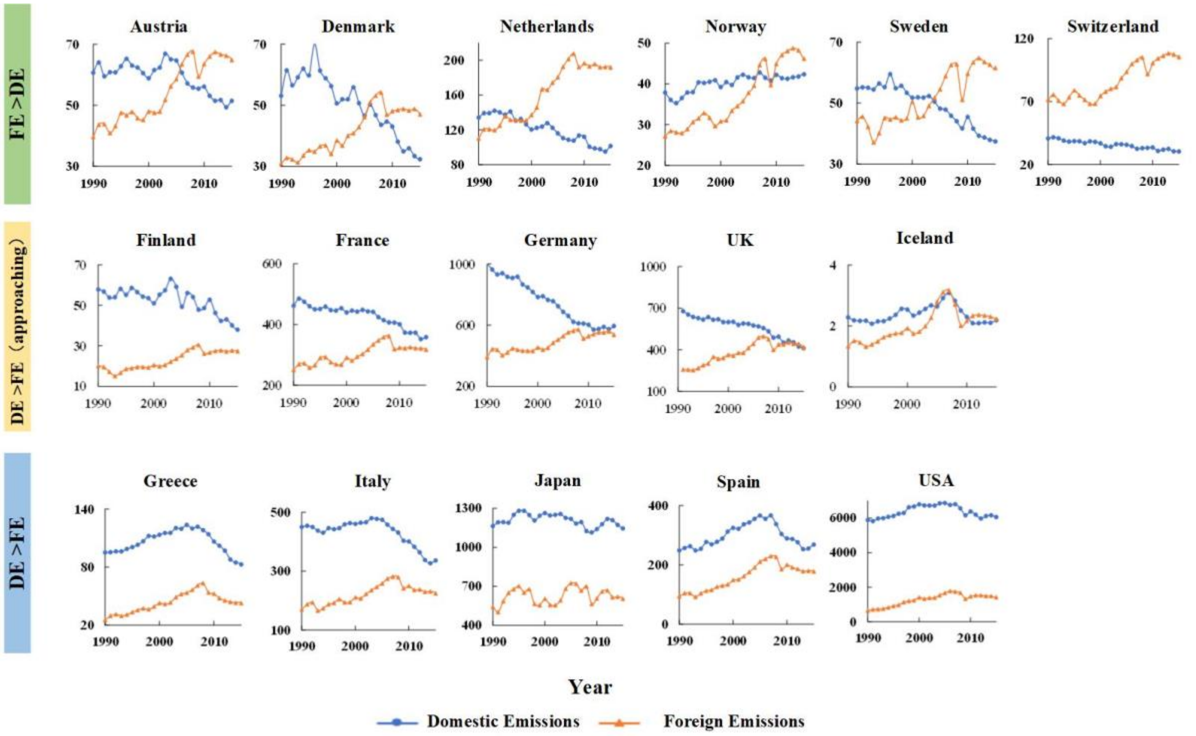

Fig. 3. Dynamics of domestic and foreign emissions in the 16 developed countries: DE, domestic emissions; FE, foreign emissions; CO_2 emissions units are Mt.

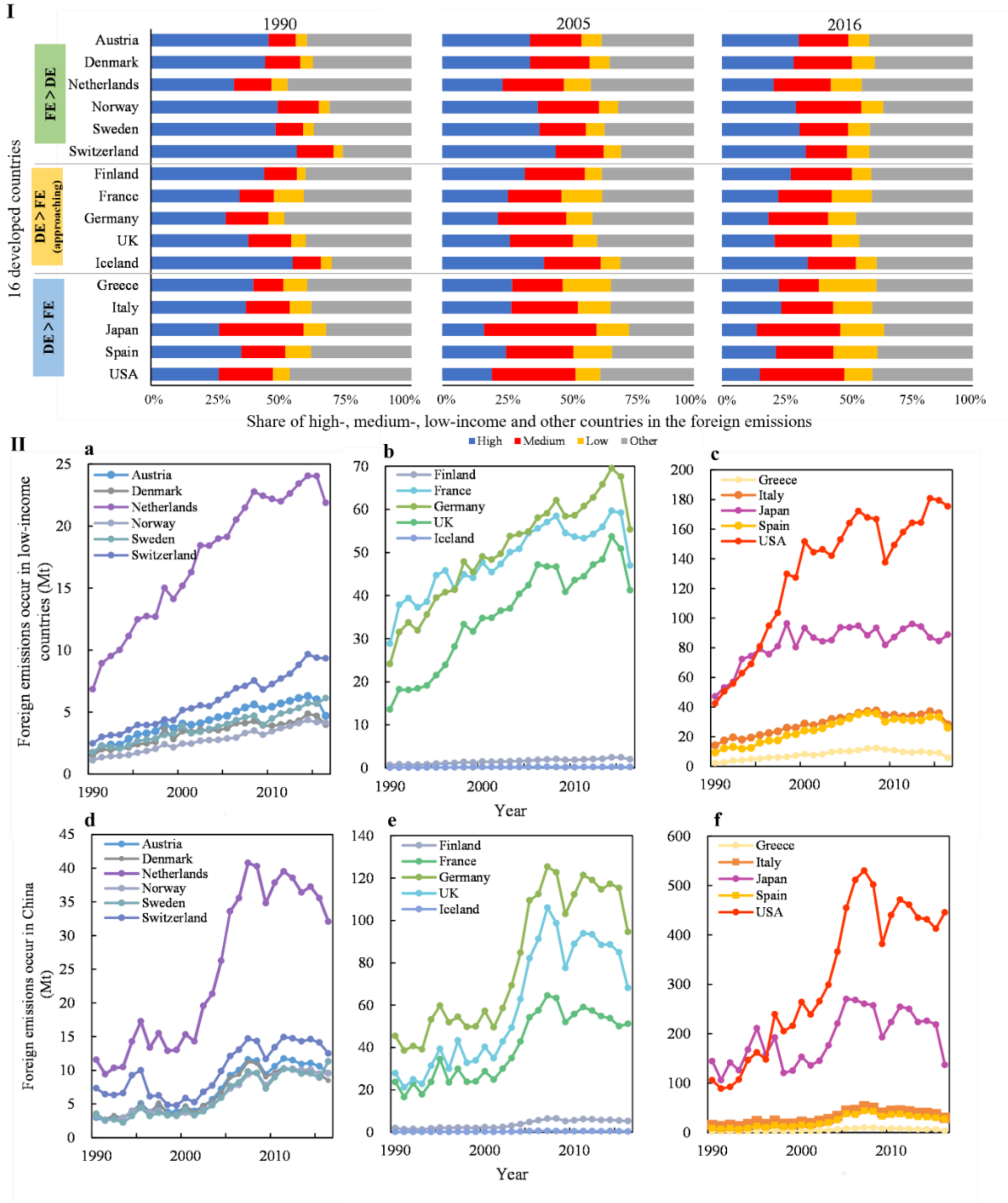

Fig. 4. Foreign emissions of 16 developed countries: (I) displays the shares of foreign emissions of 16 developed countries in high-, medium-, low-income and other countries during 1990, 2005, and 2016 (considering that the year when the CBE of most developed countries reached emissions peak was approximately 2005, which was also the year when foreign emissions exceeded domestic emissions in some countries); (II) a-c show the changes of foreign emissions of 16 developed countries in low-income countries, d-f show the changes of foreign emissions of 16 developed countries in China.

4.2 Analysis of consumption-based emissions peaking in developed countries

As mentioned above, consumption-based domestic and foreign emissions are very different. To further capture their unique driving factors, this study used an SDA to decompose the domestic and foreign emissions in developed countries. Due to the inconsistency of the peak time of consumption-based CO_2 emissions in various countries, to clearly understand the contribution differences of the driving factors before and after the peak, this paper divided the research intervals of each country into two situations in the following SDA analysis: the pre-peak stage and the post-peak stage.

4.2.1 Structural decomposition analysis of domestic emissions

The SDA results of domestic emissions changes from 1990 to peak year (i.e., pre-peak stage) and peak year to 2016 (i.e., post-peak stage) was shown in Fig. 5 and Table B3. The SDA results of domestic emissions are as follows:

(1) Domestic carbon intensity (Q_d)

Domestic carbon intensity was the decisive driver for the reduction in domestic emissions across most peaking countries (Fig. 4). In the pre-peak stage, the changes in domestic carbon intensity had a negative impact on the domestic emissions of all peaking countries (except Denmark), among which the impacts were largest in the US (-68.63%), followed by the Netherlands (-58.12%), the UK (-56.93%), and Switzerland (-55.20%). In the post-peak stage, due to the impacts of the energy crisis and environmental protection pressure, the domestic carbon intensity of most countries further decreased; thus, they showed a more significant carbon-decreasing effect, with a negative impact ranging from -82.24% (Denmark) to -12.84% (the US).

These results indicate that the differences in the contribution of domestic carbon intensity for different peaking countries are directly related to the changes in domestic carbon intensity at each stage. Taking the US as an example, the emissions reduction contribution of domestic carbon emissions intensity pre- and post-peak showed a transition from large to small. This may be explained by the fact that since the 1990s, the US has introduced many energy and emissions reduction bills, in addition to put forth a series of planning schemes for energy efficiency improvement and clean energy development, while gradually forming a sound carbon emissions reduction policy system. Specifically, the domestic carbon intensity of the US dropped from 537 tons CO_2·million USD^{-1} in 1990 to 289 tons CO_2·million USD^{-1} in 2007 (both at constant 2002 prices). Comparatively, due to the continuous and sharp decline in domestic carbon intensity in the pre-peak period, the domestic carbon emissions intensity of the US in the peak year (2007) achieved a relatively low level, thus its subsequent decline in carbon emissions has slowed down (In 2016, its domestic carbon intensity was 255 tons CO_2·million USD^{-1}, which was only 11.78% lower than that in 2007). Therefore, the further decline in domestic carbon intensity after the peak will be essential to the reduction in domestic emissions.

(2) Production structure (L)

The adjustment of the production structure was another important driver of the decline in domestic emissions of peaking countries. In the pre-peak stage, the changes in this factor maintained a certain degree of carbon reduction impact in 13 peaking countries, particularly on the domestic emissions of Iceland and Norway (-9.67% and -6.32%, respectively). Alternatively, in the post-peaking stage, its change also decreased the CO_2 emissions of Iceland, the US, the UK, Sweden, and Switzerland (-15.16%, -7.68%, -2.46%, -1.24% and -0.06%, respectively), while increase emissions of other 11 peaking countries, which partially offset the decrease caused by the reduction of carbon emissions intensity. These results implicate that these countries do not pay attention to the improvement of production technology and structure after the peak, so the role of production structure adjustment in reducing domestic emissions is opposite. In contrast, during both the pre- and post-peak stages, the adjustment of Iceland's production structure made a significant contribution to the reduction of its domestic emissions mainly due to the progress of production technology, which brought about a continuous reduction in domestic emissions. To decrease the domestic emissions, production technology adjustment is another important factor.

(3) Final demand commodity composition (ψ)

The changes in final demand commodity composition also contributed to the changes in domestic emissions to some extent, although the degree and role varied greatly among different countries. In the pre-peak stage, changes in the final demand commodity composition had a carbon-decreasing impact on the domestic emissions of most peaking countries, among which Norway (-9.81%) and Switzerland (-7.42%) were the most affected. From the perspective of domestic product demand, this was likely related to the gradual decline in the proportion of domestic products in the final demand of most countries prior to the peak. Taking Norway and Switzerland as examples, during the pre-peak period, the proportion of domestic products in the final demand of Norway decreased by 8.34%, especially in "*Petrochemical and Non-Metallic Mineral Products*", "*Other Manufacturing*", and "*Transport Equipment*" (decreasing by 35.83%, 19.07% and 18.51%, respectively). Moreover, the proportion of domestic products in the final demand of Switzerland decreased by 5.42%, and the proportion of demand for products in “*Wholesale Trade*”, “*Electrical and Machinery*”, and “*Metal Products*” decreased significantly as well (9.14%, 7.94%, and 7.75%, respectively).

In the post-peak stage, the changes in the final demand commodity composition had opposite effects on the domestic emissions of some peaking countries. For example, it had negative impacts of -0.27% and -0.21% on domestic emissions in Finland and the US, realizing the transition from carbon-increasing effect before the peak to a post-peak carbon-decreasing. Alternatively, it also had a positive impact on domestic emissions in Iceland, Switzerland, the UK, Japan, Greece, Germany, and Norway (83.03%, 8.03%, 5.12%, 2.95%, 2.83%, 1.21%, and 0.71%, respectively). These results can likely be explained by changes in the share of domestic products in the final demand of each country during the post-peak period. For Finland and the US, the share of domestic products in their final demand decreased by 3.89% and 0.14%, respectively; whereas with Iceland and Switzerland, the proportion of domestic products in their final demand increased by 5.97% and 5.32%, respectively. Thus, the latter two countries had the largest increase in the demand for products in “*Transportation*”, which increased by 32.32% and 15.38%, respectively.

(4) Final demand category composition (δ)

Although the impact of the final demand category composition was relatively small, its effects must be addressed due to its offset effect. In the pre-peaking stage, the changes in final demand category composition produced a certain degree of carbon-decreasing effects on domestic emissions in most peaking countries, among which Spain, Finland, Iceland, and the US were the most affected (-3.16%, -2.86%, -2.54%, and -2.03%, respectively). However, in the post-peaking stage, the changes in final demand category composition only had a carbon-decreasing effect on Finland, Denmark, France, Switzerland, Norway, Sweden, and the UK (-3.42%, -1.08%, -0.91%, -0.86%, -0.30%, -0.25%, and -0.22%, respectively).

The proportions of the main three types of final demand in the total demand were calculated to reveal these effects. Combining Fig. 6 and Table B4, this study found that in the pre-peak stage, the levels of Iceland, Norway, and Greece were mainly due to the decline in the proportion of final household consumption (-4.80%, -1.49%, and -0.99%, respectively); whereas France, Sweden, Austria, and Italy were mainly due to the decline in the proportion of final government consumption (-3.79%, -3.57%, -2.17%, and -1.85%, respectively). Further, the observed patterns in Spain and the US were due to the double decline in the proportion of final household and government consumption (-2.23% and -2.06% for Spain, -2.18% and -4.11% for the US), while Finland was mainly due to the decline in the proportion of fixed capital formation (-3.20%). Additionally, during the post-peak stage, the observed patterns in Switzerland were mainly due to the decline in the proportion of final household consumption (-6.63%); whereas for Finland, the UK, and Norway, the decrease in the proportion of final government consumption were the primary drivers (-5.15%, -3.83%, and -1.83%, respectively). Lastly, the shifts observed in Denmark, France, and Sweden were mainly due to the double decline in the proportion of final consumption of households and governments (-2.99% and -2.63% for Denmark, -0.98% and -0.78% for France, -2.99% and -3.83% for Sweden).

(5) Per-capita final demand and population (D and P)

The per capita final demand played a leading role in increasing domestic emissions in peaking countries. However, this effect gradually weakened in the post-peak stage, and even had a carbon-decreasing effect on domestic emissions in some countries, such as Iceland, Greece, Switzerland, Spain, and Italy (-24.05%, -21.01%, -8.08%, -7.75%, and -3.89%, respectively). This opposite effect was directly related to the decline in per capita final demand following the peak of the above five countries (changed by -24.35%, -30.23%, -9.10%, -9.02%, and -5.26%, respectively), which can be explained by the global financial crisis in 2008, and subsequent European debt crisis in 2009.

As a secondary driving factor for the increase in domestic emissions in peaking countries, the population factor had a tenuous increasing impact on the domestic emissions of almost all peaking countries pre- and post-peak. For example, in Greece, population changes contributed -3.91% to the domestic emissions after the peak, which was related to the 4.54% decrease in population caused by the number of births being less than the number of social deaths, in addition to the outflow of a large number of migrant talents in the post-peak period.

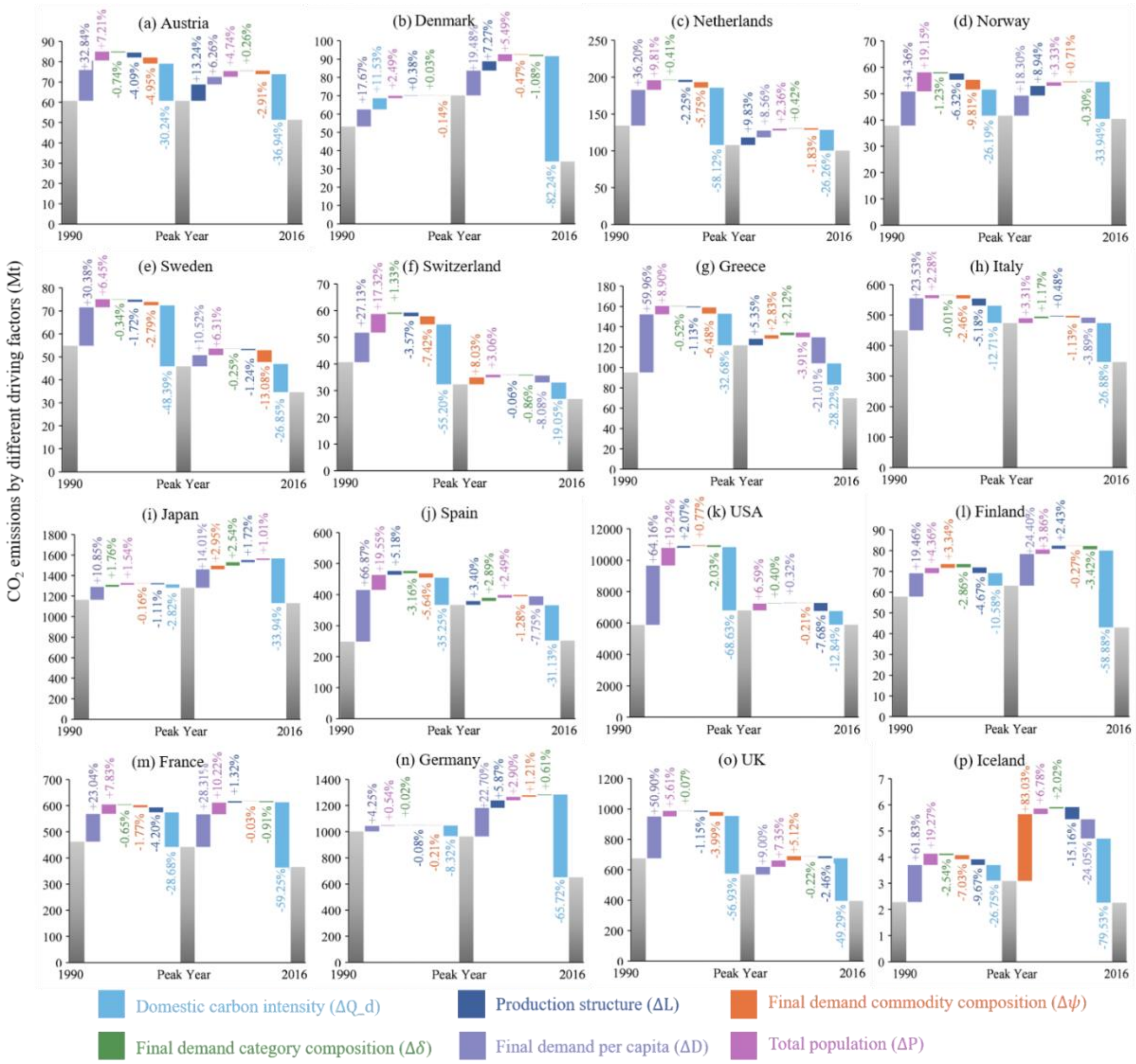

Fig. 5. SDA results for domestic emissions: gray bars reflect domestic emissions in 1990, the peak year, and 2016; whereas the length of each colored bar reflects the emissions reduction contribution of each factor.

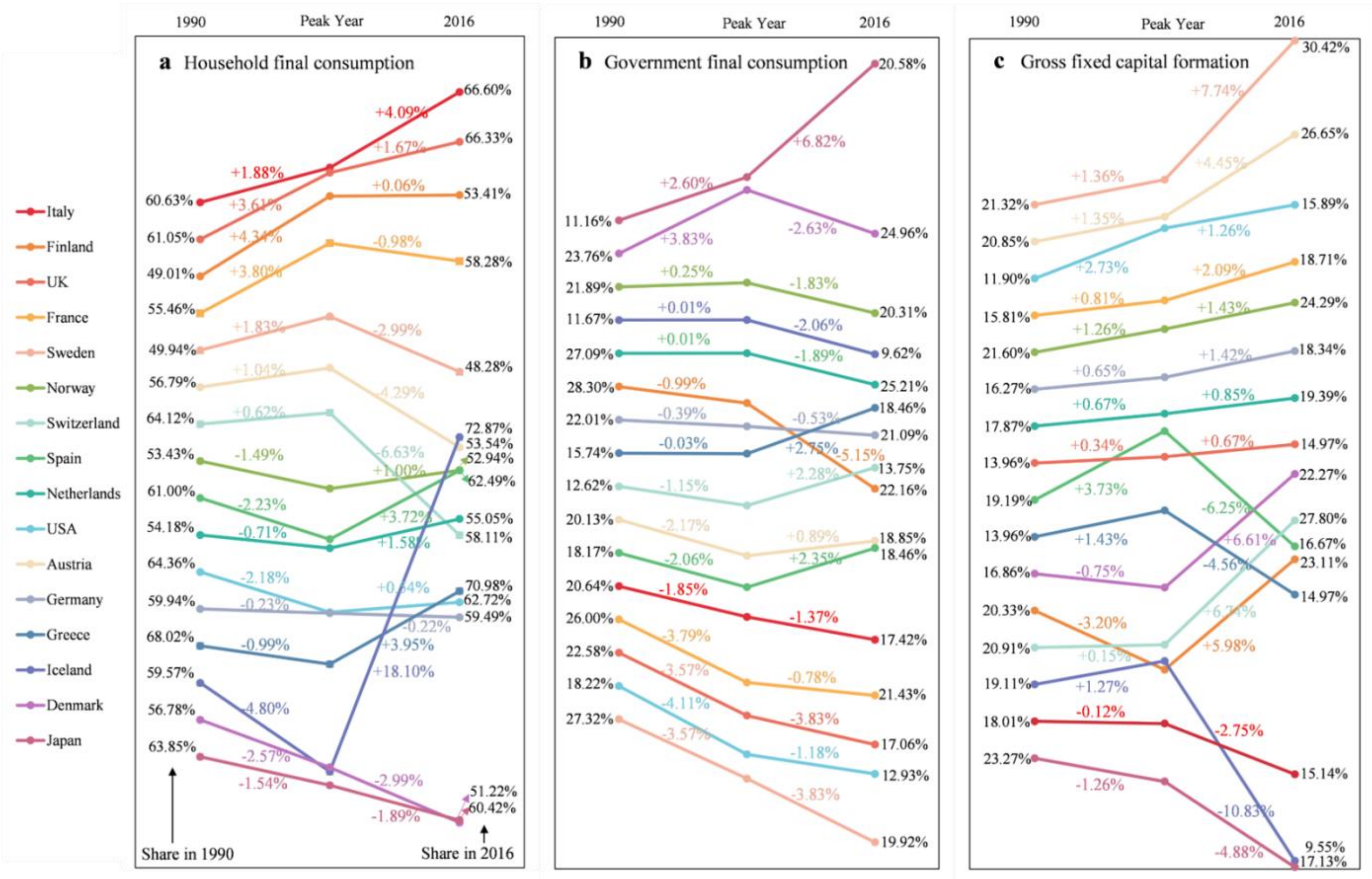

Fig. 6. Changes in the share of final demand category for the 16 developed countries: (a) changes in the share of final household consumption, (b) changes in the share of final government consumption, and (c) changes in the share of gross fixed capital formation. (Since the proportion of final household consumption, final government consumption, and total fixed capital formation accounted for > 90% of the total final demand of all the countries, this figure only presents the changes in the proportions of the above three types of final demand).

4.2.2 Structural decomposition analysis of foreign emissions

The SDA results of foreign emissions changes from 1990 to peak year and peak year to 2016 are shown in Fig. 7 and Table B5. The SDA results of domestic emissions are as follows:

(1) Foreign carbon intensity (Q_f)

The carbon intensity of foreign outputs was the dominant driving factor for the decline in foreign emissions pre- and post-peak in most countries (Fig. 7). During the pre-peak stage, the contribution to the reduction of foreign emissions in Germany, Spain, and the US exceeded -100%. In the post-peak stage, the contribution to the decrease in foreign emissions in Denmark, France, and Japan was -82.77%, -70.89%, and -65.61%, respectively. In contrast, it had a 64.26% carbon increase in Germany's foreign emissions. This contrary effect in Germany may be related to the fact that the consumption-based emissions of Germany peaked earlier (1991), while the carbon emissions intensity of other countries did not improve in the long term after Germany had entered the post-peak stage. To further understand how the changes in the carbon intensity of countries with different income types affected the foreign emissions of peaking countries, this study divided foreign carbon intensities into low-, medium-, high-income, and other countries (Fig. 7, different shades of blue bars).

1) The carbon intensity reduction in high-income countries (primarily developed countries, as shown in Fig. 8) has a significant decrease in foreign emissions before and after the peak of most countries. For example, the changes in carbon intensity in high-income countries contributed > 40% to the pre-peak reduction of foreign emissions in Norway and Switzerland, indicating that the improvement of developed countries' technological level not only contributed to the reduction of their domestic carbon emissions but reduced the foreign emissions of other developed countries through "North–North trade" as well.

2) As shown in Fig. 8, reducing carbon intensity in medium-income countries, such as China, Brazil, and South Africa, significantly reduced foreign emissions in peaking countries. For example, for the US and Japan, the carbon-decreasing effect from reducing carbon intensity in medium-income countries accounted for 54.67% and 34.96% of the total foreign carbon intensity effects in the US. Further, the corresponding proportions for Japan were 65.21% and 50.67%, respectively. These reflected that the decline in carbon intensity in medium-income countries had a prominent effect on global carbon emissions reduction.

3) Compared with pre-peak stages, the reduction of carbon intensity in low-income countries (e.g., India, Indonesia, and Egypt, as shown in Fig. 8) also contributed significantly to the reduction of post-peak foreign emissions in developed countries. It contributed -4.45%, -3.81%, -8.73%, -3.94%, -6.44%, and -8.18% to the reduction of foreign emissions after the peak in the US, Switzerland, Spain, Norway, the Netherlands, and Greece, respectively, all of which exceeded the contribution from the reduction of carbon intensity in medium- and high-income countries. These results indicated that reducing carbon intensity in low-income countries will be an important future focus for global carbon reduction.

The carbon intensity of countries with different income types had declined to varying degrees over time. However, the average carbon intensity of medium- and low-income countries was substantially higher than that of high-income countries across time. Taking 2016 as an example, the average carbon intensity of major high-, medium-, and low-income countries was 1779, 825, and 242 tons of $CO_2 \cdot$million USD^{-1}, respectively (all at constant 2002 prices). Notably, there was still a significant gap in carbon intensity among different income groups; therefore, high-income countries should provide technical and financial support for reducing carbon intensity to medium- and low-income countries.

(2) Total input structure (A^*)

As mentioned, this study defined the total technical coefficients (irrespective of source country) of all sectors in all countries as the total input structure; therefore, this factor reflected the changes in foreign emissions caused by shifts in product input of different sectors for each peaking country. In the pre-peak stage, changes in the total input structure resulted in a significant increase in the foreign emissions of all peaking countries, of which the contribution to the increase in foreign emissions from Germany, Spain, the Netherlands, and the US exceeded 40% (Fig. 7). This result was directly related to the increase in the proportion of high-carbon-intensive sectors, such as "*Petrochemical and Non-Metallic Mineral Products*", and "*Electrical and Machinery*" in the total inputs of these countries; whereas in the post-peak stage, the changes of this factor had different degrees of carbon-decreasing effects on foreign emissions in most countries (e.g., -16.11% and -12.49% on the foreign emissions of Sweden and the US, respectively). Meanwhile, in the post-peak period, their inputs in "*Petrochemical and Non-Metallic Mineral Products*", "*Electrical and Machinery*", and "*Transport*" decreased significantly (Sweden decreased by -1.24%, -1.89%, -1.17%, respectively; and the US decreased by -0.33%, -0.71%, -1.21%, respectively). In the post-peak stage, the reduction of foreign emissions by the total input structure was driven by the decline in the proportion of some high-carbon-intensive sectors of the total inputs.

(3) Intermediate and final demand source structures (C and F)

The source structures of intermediate and final demands reflected how changes in the source and share of demand for intermediate and final products in developed countries affected their foreign emissions. In the pre-and post-peak stages of peaking countries, the contributions of the above two factors to foreign emissions changes were also different (Fig. 7). In the pre-peak stage, changes in intermediate and final demand source structures significantly impacted the increase in foreign carbon emissions for most peaking countries. Alternatively, in the post-peak stage, these two factors gradually weakened the carbon-increasing effect on foreign emissions for most peaking countries. They even had a certain degree of carbon-decreasing impacts in some countries. For example, the changes in the structure of the intermediate demand source had a carbon-decreasing effect on the foreign emissions of Germany, Spain, Sweden, Norway, Austria, Italy, and Greece (-12.48%, -9.68%, -7.24%, -4.56%, -3.28%, -3.26%, and -0.10%, respectively). Comparatively, changes in the final demand source structure had a carbon-decreasing effect of -10.63%, -2.89%, -2.56%, and -2.36% on the foreign emissions of the UK, Switzerland, Greece, and Iceland, respectively. Theoretically, if all countries had the same level of production technology across all sectors, the impacts of changes in the above two factors should be neutral for any given country; however, the above results had different effects, indicating that countries providing intermediate or final products for peaking countries maintained different production technologies. Thus, when the intermediate or final products of the peaking countries were primarily derived from countries with relatively backward production technologies, the corresponding structural effect of intermediate or final demand sources was positive. In contrast, when more of these products came from countries with relatively higher production technologies, the corresponding structural effects were negative.

Generally, it was concluded here that there was a positive correlation between a country's production technology and income levels. Therefore, changes in the share of demand for products of countries with different income levels in the intermediate and final demand sources of peaking countries will lead to different changes in foreign emissions; yet, the above-mentioned net effects presented by the results obscure this detail. In this regard, according to the different income levels of countries where the source products were located, this study divided them into four types: low-, medium-, high-income, and other countries. Further, the impact of changes in the share of product sources from countries with different income levels in intermediate and final demand on the foreign emissions of the 16 peaking countries was explored as well. The results indicated that, first, in the pre-peak stage, the carbon-increasing effects of the intermediate and final demand source structures for most peaking countries were mainly driven by an increase in the share of demand for products in medium-income countries. In contrast, the demand for products in low-income countries' share changes also contributed to the growth of developed countries' foreign emissions, while changes in the share of demand for products from high-income countries mainly showed a carbon-decreasing effect, albeit relatively small. Second, in the post-peak stage, the carbon-increasing effects of most peaking countries' intermediate and final demand source structures gradually weakened, and even turned into a carbon-decreasing effect. These results were mainly due to the continuous optimization of the production technology levels for high-income countries, as well as a decrease in the share of high-income countries' roll in the intermediate and final demand products of previously peaked countries. In addition, a significant improvement in the production technologies of medium-income countries, such as China, Brazil, and South Africa, played a key role in reducing the carbon-increasing effects of intermediate and final demand structures for peaking countries. This reflected the important position of large developing countries (represented by BRICS) in the global value chain.

(4) Final demand structure (B)

As mentioned, this study defined the share of a country's total final demand from different sectors (irrespective of source country) as the country's final demand structure. Therefore, changes in this factor reflected the changes in a country's foreign emissions caused by shifts in the country's final demand for products from different sectors. In the pre-peak stage, the changes in this factor caused a small increase in the foreign emissions of most peaking countries, of which only Spain and Iceland contributed more to the carbon increase (16.05% and 10.70%, respectively; Fig. 7). However, in the post-peak stage, the changes in this factor had a certain degree of carbon-decreasing effects on foreign emissions for most peaking countries. For example, the carbon-decreasing effect on foreign emissions in the US was relatively significant (-17.75%). By analyzing the changes in the final demand of different sectors in Spain, Iceland, and the US across different periods, this study found that the former two countries had an increasing demand for high-carbon-intensive sectors, such as "*Construction*", "*Transport Equipment*", and "*Electrical and Machinery*" in the pre-peak stage. In contrast, the US had a decreasing demand for high-carbon-intensive sectors, such as "*Petrochemical and Non-Metallic Mineral Products*", and "*Transport Equipment*" in the post-peak stage, indicating that the reduced demand for high-carbon-intensive sectors in various countries drove the carbon-decreasing effects of the final demand structure.

(5) Per capita final demand and population (D and P)

The effects of per capita final demand and population factors on foreign emissions of peaking countries were similar to those of domestic emissions. In the pre-peak stage, per capita final demand played an important role regarding the increase in foreign emissions of peaking countries; however, in the post-peak stage, the impact of this factor on foreign emissions turned into a carbon-decreasing effect for a few countries, such as Iceland, Greece, Switzerland, Spain, and Italy (-20.64%, -18.63%, -9.25%, -6.41%, and -2.77%, respectively). The decline in per capita final demand can also explain these results. In addition, similar to the influence of domestic emissions, population factors had an increasing effect on foreign emissions in both the pre-and post-peak stages for almost all peaking countries; however, the population in Greece had a negative impact (-3.84%) on foreign emissions in the post-peak stage, which was closely related to the population decline of Greece.

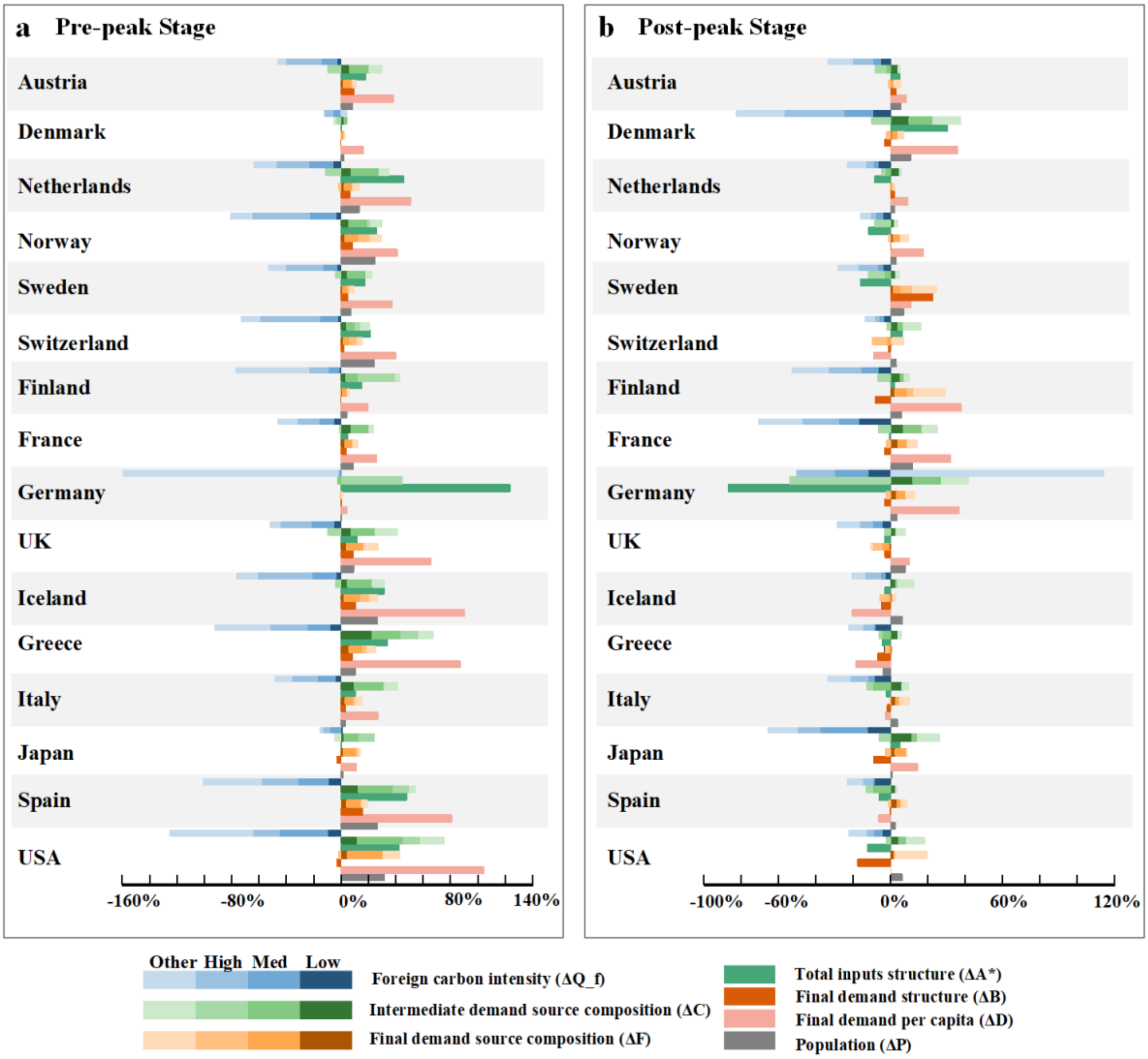

Fig. 7. SDA results for foreign emissions of countries in the: (a) pre-peak stage, (b) post-peak stage.

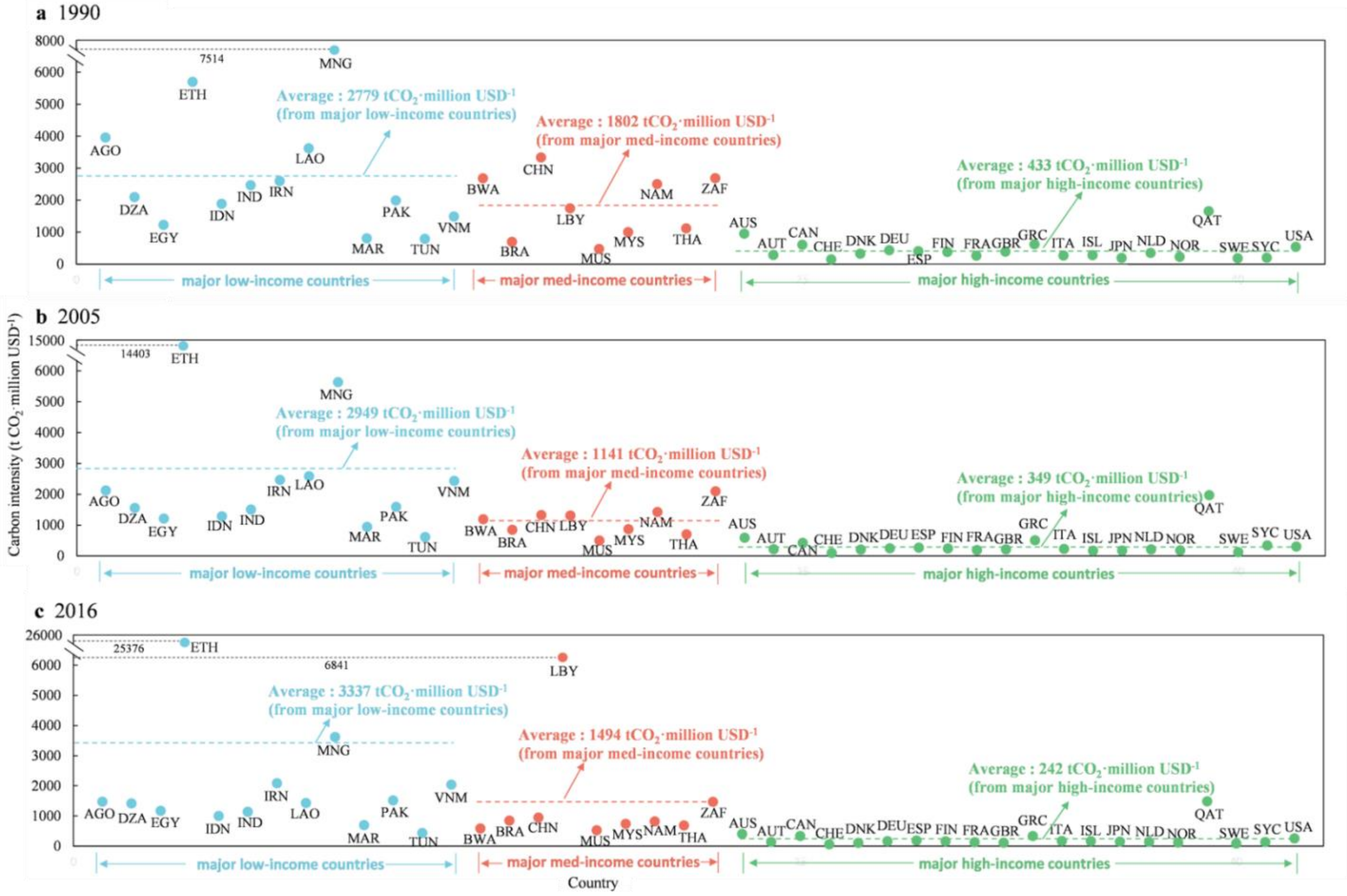

Fig. 8. Carbon intensity of the 42 countries analyzed in 1990, 2005, and 2016: blue, red, and green dots represent major low-, medium-, and high-income countries, respectively. Dotted lines in different colors represent the average carbon intensities of different types of countries. Due to apparent outliers in ETH and LBY, these two countries were excluded when calculating the average carbon intensity of each group. Each country is represented by a three-digit code, which can be found in Table B1.

5. Conclusions and Policy Implications

In the context of peaking global CO_2 emissions as soon as possible, it is increasingly important to explore true consumption-based CO_2 emissions peaks in developed countries. Accordingly, this study analyzed the consumption-based domestic and foreign CO_2 emissions of 42 countries from 1990 to 2016 based on EE-MRIO model. In addition, by constructing a SDA model for domestic and foreign emissions, this study further explored the variant driving factors of emissions changes at the pre-and post-peak stages in all 16 peaking developed countries. The main findings were as follows:

Across the study period, 16 developed countries reached their total and per capita consumption-based emissions peak between 2003 and 2008. The domestic emissions of the peaking countries had all reached their peaks. In contrast, the foreign emissions of some developed countries had not shown an obvious peak by the end of the analysis period and even showed an increasing trend. The increasing emissions transfers to medium- and low-income countries were the primary cause of rising foreign emissions in these countries.

Foreign carbon intensity, total input structure, and source structure of intermediate and final demands were the main driving forces of foreign emissions reductions in 16 peaking developed countries. The mitigation of carbon intensity within high-income countries has played a pivotal role in curbing foreign emissions among peaking developed nations. In this light, the carbon intensity of medium- and low-income countries possess a tremendous potential for carbon emission reduction. In addition, the adjustment of the total input structure has received increasing attention from most developed countries, showing different degrees of CO_2 reduction potential in the post-peak stage. Further, changes in the source structure of intermediate and final demands played a significant role in the carbon-increasing effects of peaking developed countries in the pre-peak stage; however, in the post-peak stage, this role gradually weakened.

Compared with foreign emissions, the domestic carbon intensity and per capita final demand were the main driving forces of domestic emissions reductions in 16 peaking developed countries. In contrast, most peaking countries ignored the carbon-decreasing effects of production structure adjustment. In addition, the composition of final demand commodities and categories also produced a carbon-decreasing impact in domestic emissions of developed countries by reducing the proportion of domestic products and the proportion of final consumption from households and governments.

Hence, this study puts forth the following policy discussions for global climate governance, the carbon leakages and international mitigation cooperation.

Firstly, global climate governance should focus more on CBE, as it sheds lights on trade-related emissions as well as the design of alternative mitigation policies (Fernández-Amador et al., 2017), which will be conducive to promoting the realization of climate goals proposed by the Paris Agreement from a global perspective, avoiding a further increase of global peak emissions. In this regard, we suggest that developed countries seek more CBE reduction schemes, so as to guide the green and low-carbon transition of other underdeveloped countries through consumption choices.

So far, as a meaningful instrument to motivate CBE reductions, carbon labelling schemes have already been introduced in major developed countries, such as the UK, the US, Japan, France, Canada, Switzerland, and so on. Although the research to date supports the promise of carbon labelling, it still has some controversy in terms of validity and effectiveness, for the multitude and varying "quality" of labels (Etzion, 2022), as well as the high associated costs (Taufique et al., 2022). Therefore, to make labelling systems widely credible and effective, we suggest that decision processes should engage the full range of interested and affected parties, public and private. In addition, given the current global digital economic revolution, digital carbon labelling may be another promising avenue, as it will be cheaper, easier and more effective than traditional brick-and-mortar commercial labelling.

Secondly, our results reflect that even if peaks are observed for some developed countries, the result should be approached cautiously as this outcome might also be due to the carbon leakages. That is, energy-intensive manufacturing production from developed countries might have shifted to developing countries. Ignoring this leakage issue could create a false sense of achievement and misinformation for the public and policymakers (Peters et al., 2011). Fortunately, over the past 10–15 years, several policies to deal with carbon leakage have been proposed.

To date, the most widely used anti-leakage policy is the free allocation of emission allowances in the context of tradable permit systems, most importantly the European Union Emissions Trading System (EU ETS). Although the free allocation mechanism under the EU ETS reduces the incentive to substitute domestic production with imports, since each unit of output produced domestically will receive a certain number of emission permits (Jakob, 2021), numerous studies argued that the mechanism is problematic as the policy limits emissions only in the EU—rather than globally (Martin et al., 2014; Koch and Mama, 2019; Naegele and Zaklan, 2019). In addition, another measure widely discussed recently to address leakage is carbon border adjustment mechanism (CBAM); however, the extent to which the CBAM can address carbon leakage was highly controversial, as it might lead to "trade wars" and worsen relationships, making climate cooperation more difficult to achieve (Mörsdorf, 2022; Böhringer et al., 2022). Based on these, we believe that an effective way to address carbon leakage issues is to build a global carbon market. Notably, the global carbon market we propose here is not a set of fully linked markets—that would be too difficult, since there are around 190 countries in the world—but a set of separate carbon markets with varying degrees of linkage, which in aggregate enforced the required global quantity of emissions cap, would be sufficient.

Thirdly, our findings also suggest that more attention should be paid to the carbon intensity in medium- and low-income countries, as it has great potential for reducing the foreign emissions of developed countries. However, these countries, especially low-income countries, still face many obstacles in reducing carbon intensity, such as backward technology and large funding gap (Hoekstra et al., 2016). Therefore, effective mitigation of climate change will require extensive international assistance and cooperation between developed and underdeveloped countries (Dietz and Zhao, 2011; Keohane and Victor, 2016; Wang et al., 2023).

With respect to international assistance and cooperation, we observe two different approaches. First, transfer clean technology to promote renewable energy use and energy efficiency in underdeveloped countries. Incentives for such technology flows are currently provided under the Kyoto Protocol through the Clean Development Mechanism (Popp, 2011; Murphy et al., 2015; Cui et al., 2020), which offers polluters in developed countries credits for financing projects that reduce emissions in underdeveloped countries (Gandenberger et al., 2016). Second, build climate finance to provide financial support for climate actions in underdeveloped countries. Although at the United Nations Climate Summit in Copenhagen in 2009, developed countries promised to channel US$100 billion per year to underdeveloped countries by 2020 (Donner et al., 2011); however, some worrying trends have been widely acknowledged, such as the failed promise of climate finance, the varying "quality" of climate finance, and the underfunding of multilateral climate funds (Chowdhury and Sundaram, 2022). Further, COVID-19 has worsened the situation (Timperley, 2021). Therefore, we argue that as the pandemic passes, real plans must be developed and implemented to achieve these financing goals based on realistic assessments of developing countries' needs. Specifically, to agree on new climate finance, both developed and developing countries could consider taking advice from a trusted third party that already has a role in setting data standards, but is not involved in international diplomacy. In summary, it is time to begin that effort with ambition and accountability in order to build enduring trust and resilience.

CRediT authorship contribution statement

Zhen Wang: Methodology, Software, Data curation, Formal analysis, Writing – original draft, Visualization. **Hao-Ben Yan:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Xue Gao:** Methodology, Investigation, Writing – original draft. **Qiao-Mei Liang:** Writing – review & editing. **Zhifu Mi:** Writing – review & editing. **Lan-Cui Liu:** Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Statement

Data will be made available on request.

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Appendix A. Model derivation

1. Detailed derivation of EE-MRIO model

Let there be m countries or regions (labelled r or s), and n sectors (labelled i or j) in each country or region. Define $\boldsymbol{Z}$ as the intermediate input matrix, where $\boldsymbol{Z^{rs}}$ is the flow of commodities from country r to country s, and z_{ij}^{rs} is the flow of commodities from sector i in country r to sector j in country s. Meanwhile, let $\boldsymbol{Y}$ be the final demand matrix, where $\boldsymbol{Y^{rs}}$ is the final demand in country s for the output of country r, and y_{id}^{rs} is the d^{th} final demand in country s for the output of sector i in country r. The corresponding matrices are described as follows:

$$\boldsymbol{Z} = \begin{bmatrix} \boldsymbol{Z^{11}} & \cdots & \boldsymbol{Z^{1s}} & \cdots & \boldsymbol{Z^{1m}} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \boldsymbol{Z^{r1}} & \cdots & \boldsymbol{Z^{rs}} & \cdots & \boldsymbol{Z^{rm}} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \boldsymbol{Z^{m1}} & \cdots & \boldsymbol{Z^{ms}} & \cdots & \boldsymbol{Z^{mm}} \end{bmatrix}, \text{ with } \boldsymbol{Z^{rs}} = \begin{bmatrix} z_{11}^{rs} & \cdots & z_{1j}^{rs} & \cdots & z_{1n}^{rs} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ z_{i1}^{rs} & \cdots & z_{ij}^{rs} & \cdots & z_{in}^{rs} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ z_{n1}^{rs} & \cdots & z_{nj}^{rs} & \cdots & z_{nn}^{rs} \end{bmatrix};$$

$$\boldsymbol{Y} = \begin{bmatrix} \boldsymbol{Y^{11}} & \cdots & \boldsymbol{Y^{1s}} & \cdots & \boldsymbol{Y^{1m}} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ \boldsymbol{Y^{r1}} & \cdots & \boldsymbol{Y^{rs}} & \cdots & \boldsymbol{Y^{rm}} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ \boldsymbol{Y^{m1}} & \cdots & \boldsymbol{Y^{ms}} & \cdots & \boldsymbol{Y^{mm}} \end{bmatrix}, \text{ with } \boldsymbol{Y^{rs}} = \begin{bmatrix} y_{11}^{rs} & \cdots & y_{1d}^{rs} & \cdots & y_{16}^{rs} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ y_{i1}^{rs} & \cdots & y_{id}^{rs} & \cdots & y_{i6}^{rs} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ y_{n1}^{rs} & \cdots & y_{nd}^{rs} & \cdots & y_{n6}^{rs} \end{bmatrix}.$$

Define the technical coefficients as $a_{ij}^{rs} = {z_{ij}^{rs}}/{x_j^r}$. Following the traditional setup of an MRIO model, the output of sector i in country r (x_i^r) is distributed to intermediate and final demand according to Eq. (1):

$$x_i^r = \sum_s \sum_j z_{ij}^{rs} + \sum_s \sum_d y_{id}^{rs} = \sum_s \sum_j a_{ij}^{rs} x_j^r + \sum_s \sum_d y_{id}^{rs}. \quad (1)$$

This can be rewritten in stacked matrix form for all industries and countries (Eq. (2)):

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

where $\boldsymbol{X}=\begin{bmatrix}\boldsymbol{X}^{1}\\ \vdots\\ \boldsymbol{X}^{r}\\ \vdots\\ \boldsymbol{X}^{m}\end{bmatrix}$, with $\boldsymbol{X}^{r}=\begin{bmatrix}x_1^r\\ \vdots\\ x_i^r\\ \vdots\\ x_n^r\end{bmatrix}$, and x_i^r represents the total output of sector i in country r. In the Leontief inverse matrix $(\boldsymbol{I}-\boldsymbol{A})^{-1}$, $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{A}$ is the direct consumption coefficient matrix, and $\boldsymbol{Y}$ is the final demand matrix. Furthermore, this study introduced a carbon emissions intensity matrix $\boldsymbol{Q}=\begin{bmatrix}\boldsymbol{Q}^{1}\\ \vdots\\ \boldsymbol{Q}^{s}\\ \vdots\\ \boldsymbol{Q}^{m}\end{bmatrix}$, with $\boldsymbol{Q}^{s}=\begin{bmatrix}q_1^s\\ \vdots\\ q_j^s\\ \vdots\\ q_n^s\end{bmatrix}$, q_j^s represents the carbon emissions per unit output of sector j in country s, and multiplies its diagonal matrix $\widehat{\boldsymbol{Q}}$ to the left by the corresponding total output $\boldsymbol{X}$ in Eq. (2) to obtain the EE-MRIO, as shown in Eq. (3):

$$\boldsymbol{E}=\widehat{\boldsymbol{Q}}(\boldsymbol{I}-\boldsymbol{A})^{-1}\boldsymbol{Y}\,. \tag{3}$$

2. Detailed derivation of the factor decomposition of foreign emissions

2.1 Intermediate demand source structure ($\boldsymbol{C}^{s}$)

The intermediate sourcing shares matrix $\boldsymbol{C}^{s}$ was obtained from the relationship $\boldsymbol{Z}^{s}=\boldsymbol{C}^{s}\otimes\boldsymbol{Z}^{*,s}$ ($\otimes$ represents the Hadamard product), where the intermediate input matrix $\boldsymbol{Z}^{s}=\begin{bmatrix}\boldsymbol{0} & \cdots & \boldsymbol{Z}^{1s} & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots & \iddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{Z}^{rs} & \cdots & \boldsymbol{0}\\ \vdots & \iddots & \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{Z}^{ms} & \cdots & \boldsymbol{0}\end{bmatrix}$, with $\boldsymbol{Z}^{rs}=\begin{bmatrix}z_{11}^{rs} & \cdots & z_{1j}^{rs} & \cdots & z_{1n}^{rs}\\ \vdots & \ddots & \vdots & \iddots & \vdots\\ z_{i1}^{rs} & \cdots & z_{ij}^{rs} & \cdots & z_{in}^{rs}\\ \vdots & \iddots & \vdots & \ddots & \vdots\\ z_{n1}^{rs} & \cdots & z_{nj}^{rs} & \cdots & z_{nn}^{rs}\end{bmatrix}$, z_{ij}^{rs} represents the intermediate input of sector i in country r to sector j in country s; the intermediate input matrix irrespective of source country $\boldsymbol{Z}^{*,s}=\begin{bmatrix}\boldsymbol{0} & \cdots & \boldsymbol{Z}^{*s} & \cdots & \boldsymbol{0}\\ \vdots & \ddots & \vdots & \iddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{Z}^{*s} & \cdots & \boldsymbol{0}\\ \vdots & \iddots & \vdots & \ddots & \vdots\\ \boldsymbol{0} & \cdots & \boldsymbol{Z}^{*s} & \cdots & \boldsymbol{0}\end{bmatrix}$, with $\boldsymbol{Z}^{*s}=$

$\begin{bmatrix} z_{11}^{*s} & \cdots & z_{1j}^{*s} & \cdots & z_{1n}^{*s} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ z_{i1}^{*s} & \cdots & z_{ij}^{*s} & \cdots & z_{in}^{*s} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ z_{n1}^{*s} & \cdots & z_{nj}^{*s} & \cdots & z_{nn}^{*s} \end{bmatrix}$, $z_{ij}^{*s} = \sum_r z_{ij}^{rs}$ represents the intermediate input of sector i in all countries, to sector j in country s; thus, $\boldsymbol{C^s} = \begin{bmatrix} \mathbf{0} & \cdots & \boldsymbol{C^{1s}} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{C^{rs}} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{C^{ms}} & \cdots & \mathbf{0} \end{bmatrix} =$ $\begin{bmatrix} \mathbf{0} & \cdots & \boldsymbol{Z^{1s}}/\boldsymbol{Z^{*s}} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Z^{rs}}/\boldsymbol{Z^{*s}} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Z^{ms}}/\boldsymbol{Z^{*s}} & \cdots & \mathbf{0} \end{bmatrix}$ represents the share of intermediate inputs for all sectors in country s (i.e., intermediate demand source structure of country s).

2.2 Total input structure ($\boldsymbol{A^{*s}}$)

The total input structure matrix $\boldsymbol{A^{*s}}$ was obtained from the relationship $\boldsymbol{Z^s}\widehat{\boldsymbol{x^s}}^{-1} = \boldsymbol{C^s} \otimes \boldsymbol{Z^{*,s}}\widehat{\boldsymbol{x^s}}^{-1}$, where $\widehat{\boldsymbol{x^s}}^{-1}$ is the diagonal inverse matrix of country s' total outputs; thus, $\boldsymbol{A^{*s}} =$ $\boldsymbol{Z^{*,s}}\widehat{\boldsymbol{x^s}}^{-1} = \begin{bmatrix} \mathbf{0} & \cdots & \boldsymbol{Z^{*s}}\widehat{\boldsymbol{x^s}}^{-1} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Z^{*s}}\widehat{\boldsymbol{x^s}}^{-1} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Z^{*s}}\widehat{\boldsymbol{x^s}}^{-1} & \cdots & \mathbf{0} \end{bmatrix}$ represents the technical coefficients regardless of source country for all sectors in country s (i.e., total input structure of country s). Specifically, the $*$ stands for the sum of the index that it replaces.

2.3 Final demand source structure ($\boldsymbol{F^s}$)

The final demand share matrix F^s was obtained from the relationship $\boldsymbol{Y^s} = \boldsymbol{F^s} \otimes \boldsymbol{Y^{*,s}}$, where the final demand matrix $\boldsymbol{Y^s} = \begin{bmatrix} \mathbf{0} & \cdots & \boldsymbol{Y^{1s}} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Y^{rs}} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Y^{ms}} & \cdots & \mathbf{0} \end{bmatrix}$, with $\boldsymbol{Y^{rs}} = \begin{bmatrix} y_1^{rs} \\ \vdots \\ y_i^{rs} \\ \vdots \\ y_n^{rs} \end{bmatrix}$, y_i^{rs}

represents the total final demand of country s for sector i in country r; the final demand matrix irrespective of source country $\boldsymbol{Y}^{*,s} = \begin{bmatrix} \mathbf{0} & \cdots & \boldsymbol{Y}^{*s} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Y}^{*s} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Y}^{*s} & \cdots & \mathbf{0} \end{bmatrix}$, with $\boldsymbol{Y}^{*s} = \begin{bmatrix} y_1^{*s} \\ \vdots \\ y_i^{*s} \\ \vdots \\ y_n^{*s} \end{bmatrix}$, y_i^{*s} represents the total final demand of country s for sector i in all countries; thus, $\boldsymbol{F}^s = \begin{bmatrix} \mathbf{0} & \cdots & \boldsymbol{F}^{1s} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{F}^{rs} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{F}^{ms} & \cdots & \mathbf{0} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \cdots & \boldsymbol{Y}^{1s}/\boldsymbol{Y}^{*s} & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Y}^{rs}/\boldsymbol{Y}^{*s} & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{Y}^{ms}/\boldsymbol{Y}^{*s} & \cdots & \mathbf{0} \end{bmatrix}$ represents the share of final demands for all sectors in country s (i.e., final demand source structure of country s).

2.4 Final demand structure ($\boldsymbol{B}^s$)

The final demand structure matrix $\boldsymbol{B}^s = \begin{bmatrix} \mathbf{0} & \cdots & \boldsymbol{b}^s & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{b}^s & \cdots & \mathbf{0} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \boldsymbol{b}^s & \cdots & \mathbf{0} \end{bmatrix}$, with $\boldsymbol{b}^s = \begin{bmatrix} b_1^s \\ \vdots \\ b_i^s \\ \vdots \\ b_n^s \end{bmatrix}$, and $b_i^s = y_i^{*s} / \sum_i y_i^{*s}$ represents the share of sector i in total final demand of country s.

Appendix B. Supplementary data

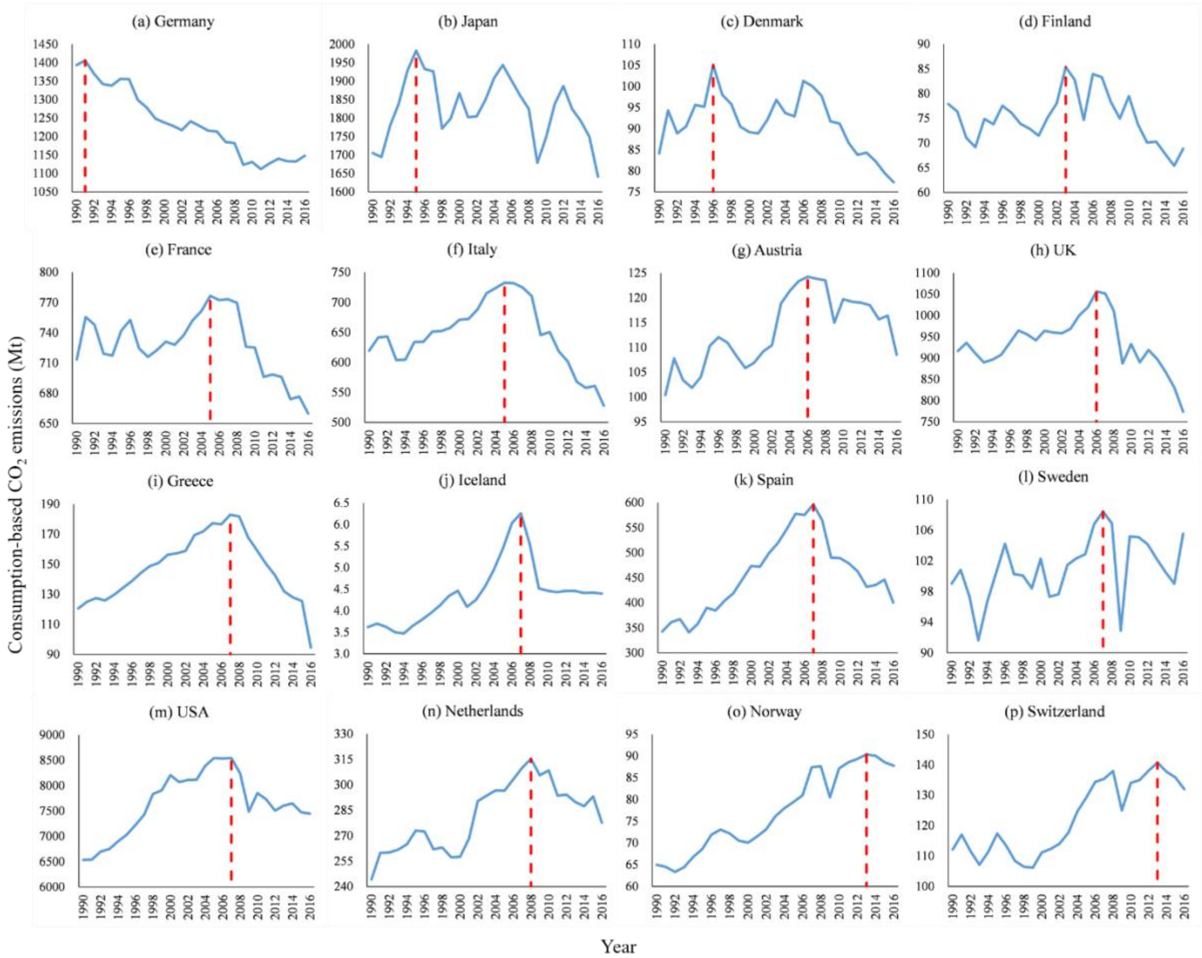

Fig. B1. Trends of consumption-based CO_2 emissions for the 16 peak countries (sorted by peak year): blue line represents the CO_2 emissions trends on the consumption side, and red dotted line corresponds to the peak year and peak value.

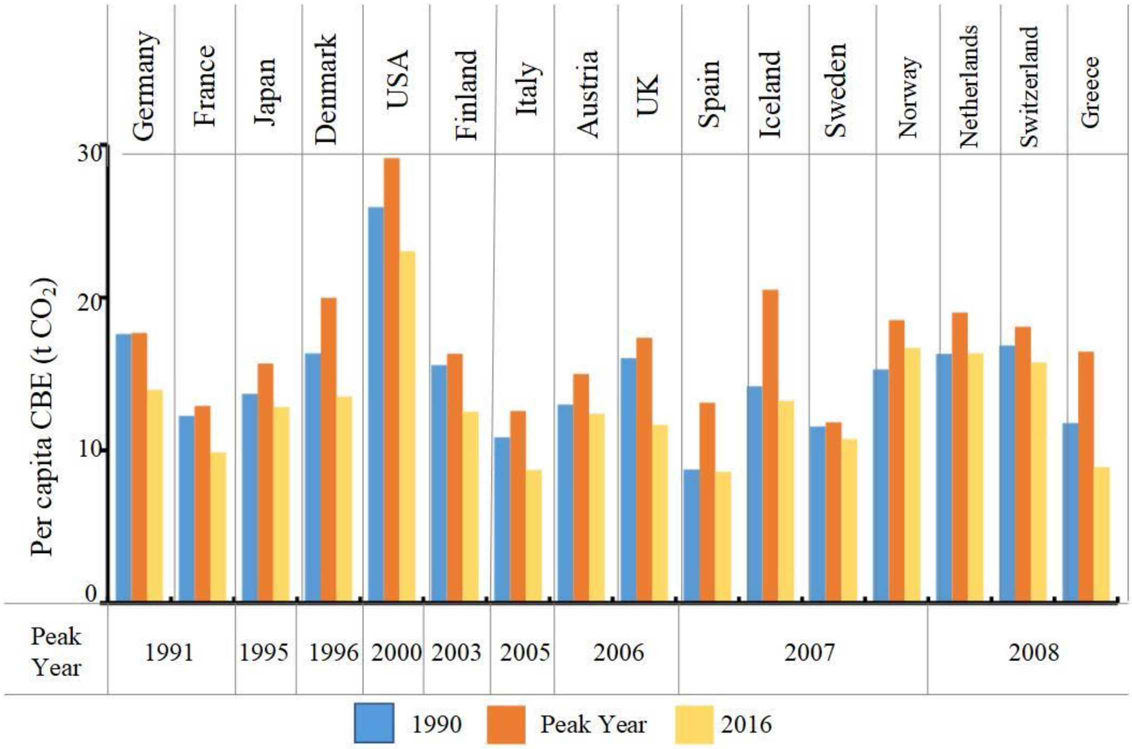

Fig. B2. Dynamics of per capita CBE in the 16 developed countries: CBE refers to consumption-based CO_2 emissions, peak year refers to peak per capita CBE.

Table B1 Alphabetized country list.

Low-income countries			**Medium-income countries**			**High-income countries**		
Number	Country	Code	Number	Country	Code	Number	Country	Code
1	Algeria	DZA	1	Botswana	BWA	1	Australia	AUS
2	Angola	AGO	2	Brazil	BRA	2	Austria	AUT
3	Egypt	EGY	3	China	CHN	3	Canada	CAN
4	Ethiopia	ETH	4	Libya	LBY	4	Denmark	DNK
5	India	IND	5	Malaysia	MYS	5	Finland	FIN
6	Indonesia	IDN	6	Mauritius	MUS	6	France	FRA
7	Iran	IRN	7	Namibia	NAM	7	Germany	DEU
8	Laos	LAO	8	South Africa	ZAF	8	Greece	GRC
9	Mongolia	MNG	9	Thailand	THA	9	Iceland	ISL
10	Morocco	MAR				10	Italy	ITA
11	Pakistan	PAK				11	Japan	JPN
12	Tunisia	TUN				12	Netherlands	NLD
13	Vietnam	VNM				13	Norway	NOR
						14	Qatar	QAT
						15	Seychelles	SYC
						16	Spain	ESP
						17	Sweden	SWE
						18	Switzerland	CHE
						19	United Kingdom	GBR
						20	United States	USA

Notes: According to the new World Bank's country income classification criteria (2022–2023), this study combined low- and lower-middle-income countries as "low-income countries", and divided each economy into three types: low-income (per capita GNI ⩽ US$ 1,085), medium-income (per capita GNI between US$ 1,086 and US$ 13,205), and high-income countries (per capita GNI ⩾ US$ 13,206).

Table B2 Sector list created by merging 26 sectors from the Eora26 database.

Number	Sectors in this study	Sectors in Eora26
1	Agriculture	Agriculture Fishing
2	Mining and Quarrying	Mining and Quarrying
3	Food & Beverages	Food & Beverages
4	Textiles and Wearing Apparel	Textiles and Wearing Apparel
5	Wood and Paper	Wood and Paper
6	Petrochemical and Non-Metallic Mineral Products	Petroleum, Chemical and Non-Metallic Mineral Products
7	Metal Products	Metal Products
8	Electrical and Machinery	Electrical and Machinery
9	Transport Equipment	Transport Equipment
10	Other Manufacturing	Recycling Other Manufacturing
11	Electricity, Gas and Water	Electricity, Gas and Water
12	Construction	Construction
13	Wholesale Trade	Wholesale Trade
14	Retail Trade	Retail Trade
15	Transport	Transport
16	Others	Maintenance and Repair Hotels and Restaurants Post and Telecommunications Financial Intermediation and Business Activities Public Administration Education, Health and Other Services Private Households Others Re-export & Re-import

Notes: Sector list was created by merging 26 sectors from the Eora26 database

Table B3 Domestic CO_2 emissions and percent change of decomposition factors for the 16 developed countries.

	Domestic CO_2 Emissions (Mt)			Decomposition (%)											
	1990	Peak Year	2016	Q_d		L		ψ		δ		D		P	
				Pre.	Post.	Pre.	Post.	Pre.	Post.	Pre.	Post.	Pre.	Post.	Pre.	Post.
AUT	60.70	60.73	51.41	-30.23	-36.94	-4.09	13.24	-4.95	-2.91	-0.74	0.26	32.84	6.26	7.21	4.74
DNK	53.14	70.12	33.97	11.53	-82.24	0.38	7.27	-0.14	-0.47	0.03	-1.08	17.67	19.48	2.49	5.49
FIN	57.85	63.09	42.97	-10.58	-58.88	-4.67	2.43	3.34	-0.27	-2.86	-3.42	19.46	24.40	4.36	3.86
FRA	462.19	441.74	365.81	-28.68	-59.25	-4.20	1.32	-1.77	-0.03	-0.65	-0.91	23.04	28.31	7.83	10.22
DEU	1001.91	963.89	651.34	-8.32	-65.72	-0.08	5.87	-0.21	1.21	0.02	0.61	4.25	22.70	0.54	2.90
GRC	95.13	121.82	69.63	-32.68	-28.22	-1.13	5.35	-6.48	2.83	-0.52	2.12	59.96	-21.01	8.90	-3.91
ISL	2.28	3.09	2.26	-26.75	-79.53	-9.67	-15.16	-7.03	83.03	-2.54	2.02	61.83	-24.05	19.27	6.78
ITA	449.76	474.25	346.51	-12.71	-26.88	-5.18	0.48	-2.46	-1.13	-0.01	1.17	23.53	-3.89	2.28	3.31
JPN	1163.97	1281.02	1132.22	-2.82	-33.94	-1.11	1.72	-0.16	2.95	1.76	2.54	10.85	14.01	1.54	1.10
NLD	134.14	107.72	100.27	-58.12	-26.26	-2.25	9.83	-5.75	-1.83	0.41	0.42	36.20	8.56	9.81	2.36
NOR	37.86	41.63	40.40	-26.19	-33.94	-6.32	8.94	-9.81	0.71	-1.23	-0.30	34.36	18.30	19.15	3.33
ESP	248.65	366.87	251.79	-35.25	-31.13	5.18	3.40	-5.64	-1.28	-3.16	2.89	66.87	-7.75	19.55	2.49
SWE	54.84	45.90	34.61	-48.39	-26.85	-1.72	-1.24	-2.79	-13.08	-0.34	-0.25	30.48	10.52	6.45	6.31
CHE	40.69	32.39	26.90	-55.20	-19.05	-3.57	-0.06	-7.42	8.03	1.33	-0.86	27.13	-8.08	17.32	3.06
GBR	675.86	569.08	395.46	-56.93	-49.29	-1.15	-2.46	-3.99	5.12	0.07	-0.22	40.59	9.00	5.61	7.35
USA	5884.32	6801.01	5889.02	-68.63	-12.84	2.07	-7.68	0.77	-0.21	-2.03	0.40	64.16	0.32	19.24	6.59

Notes: Domestic CO_2 emissions for 1990, the peak years, and 2016 are presented. Changes from 1990 to the peak year, and from the peak year to 2016 are decomposed into domestic carbon intensity (Q_d), production structure (L), final demand commodity composition (ψ), final demand category composition (δ), final demand per capita (D), and population (P). Positive signs indicate increased emissions; negative signs represent decreased emissions.

Table B4 Share of six final demand types in total final demand of the 16 developed countries.

	D1 (%)			D2 (%)			D3 (%)			D4 (%)			D5 (%)			D6 (%)		
	1990	**Peak Year**	**2016**	**1990**	**Peak Year**	**2016**	**1990**	**Peak Year**	**2016**	**1990**	**Peak Year**	**2016**	**1990**	**Peak Year**	**2016**	**1990**	**Peak Year**	**2016**
AUT	56.79	57.83	53.54	1.72	1.45	0.12	20.13	17.96	18.85	20.85	22.20	26.65	0.32	0.42	0.63	0.20	0.14	0.21
DNK	56.78	54.21	51.22	2.02	1.52	0.40	23.76	27.59	24.96	16.86	16.11	22.27	0.39	0.39	0.94	0.19	0.18	0.21
FIN	49.01	53.35	53.41	1.95	2.11	1.32	28.30	27.31	22.16	20.33	17.13	23.11	0.40	0.09	0.00	0.01	0.00	0.01
FRA	55.46	59.26	58.28	2.27	1.27	0.33	26.00	22.21	21.43	15.81	16.62	18.71	0.42	0.60	1.20	0.04	0.04	0.06
DEU	59.94	59.71	59.49	1.70	1.66	1.03	22.01	21.62	21.09	16.27	16.92	18.34	-0.02	-0.01	-0.05	0.09	0.11	0.10
GRC	68.02	67.03	70.98	0.96	0.93	0.32	15.74	15.71	18.46	14.73	16.16	11.60	0.55	0.17	-1.35	0.00	0.00	0.00
ISL	59.57	54.77	72.87	7.02	8.94	6.48	11.67	11.68	9.62	19.11	20.38	9.55	0.31	0.40	0.06	2.31	3.83	1.43
ITA	60.63	62.51	66.60	0.32	0.32	0.23	20.64	18.79	17.42	18.01	17.89	15.14	0.11	0.10	0.23	0.30	0.38	0.37
JPN	63.85	62.31	60.42	0.77	0.87	1.35	11.16	13.76	20.58	23.27	22.01	17.13	0.21	0.14	0.04	0.75	0.91	0.49
NLD	54.18	53.47	55.05	0.66	0.85	0.16	27.09	27.10	25.21	17.87	18.54	19.39	0.19	0.04	0.19	0.00	0.00	0.00
NOR	53.43	51.94	52.94	1.56	1.64	0.57	21.89	22.14	20.31	21.60	22.86	24.29	1.53	1.41	1.87	0.01	0.01	0.01
ESP	61.00	58.77	62.49	0.45	0.73	0.69	18.17	16.11	18.46	19.19	22.92	16.67	0.39	0.34	0.83	0.80	1.13	0.86
SWE	49.94	51.77	48.78	1.28	1.43	0.42	27.32	23.75	19.92	21.32	22.68	30.42	0.11	0.30	0.38	0.03	0.06	0.09
CHE	64.12	64.74	58.11	1.89	2.02	0.53	12.62	11.47	13.75	20.91	21.06	27.80	0.02	-0.11	-1.11	0.44	0.83	0.93
GBR	61.05	64.66	66.33	1.91	1.76	1.06	22.58	18.80	17.06	13.96	14.30	14.97	0.43	0.35	0.44	0.07	0.13	0.14
USA	64.36	62.18	62.72	2.63	3.51	3.43	18.22	14.11	12.93	11.90	14.63	15.89	2.29	4.38	3.43	0.60	1.19	1.60

Notes: Shares of the six final demand types of total final demand in 1990, the peak years, and 2016. (D1) Household final consumption, (D2) Non-profit institutions serving households, (D3) Government final consumption, (D4) Gross fixed capital formation, (D5) Changes in inventories, (D6) Acquisitions less disposable valuables.

Table B5 Foreign CO_2 emissions and percent change of decomposition factors in the 16 developed countries.

	Foreign CO_2 Emissions (Mt)			**Decomposition (%)**													
	1990	**Peak Year**	**2016**	**Q_f**		**C**		**A***		**F**		**B**		**D**		**P**	
				Pre.	**Post.**	**Pre.**	**Post.**	**Pre.**	**Post.**	**Pre.**	**Post.**	**Pre.**	**Post.**	**Pre.**	**Post.**	**Pre.**	**Post.**
AUT	39.69	63.50	57.13	-45.94	-33.57	20.67	-3.28	17.93	5.31	11.48	4.38	9.23	3.00	38.28	8.57	8.36	5.54
DNK	30.95	34.94	43.31	-7.94	-82.77	-1.28	27.72	0.72	30.57	2.65	4.99	-0.24	-3.29	16.64	35.98	2.35	10.75
FIN	20.04	22.28	25.90	-77.17	-52.99	43.17	3.21	15.36	2.39	5.61	27.83	-0.05	-8.23	20.04	37.92	4.19	6.16
FRA	251.21	334.92	293.88	-46.03	-70.89	22.61	18.56	5.08	-0.56	12.40	11.98	3.83	-3.26	26.30	32.38	9.14	11.97
DEU	391.52	442.27	496.20	-158.86	64.26	42.02	-12.48	123.71	-87.11	0.42	10.44	0.49	-3.17	4.60	36.84	0.59	3.41
GRC	25.36	61.02	24.92	-92.01	-22.57	67.43	-0.10	34.07	-4.59	25.24	-2.56	8.17	-6.87	87.26	-18.63	10.47	-3.84
ISL	1.34	3.17	2.14	-76.16	-20.55	27.56	12.71	31.61	-3.08	26.60	-2.36	10.70	-4.99	90.35	-20.64	26.81	6.45
ITA	169.75	258.33	181.40	-48.65	-33.59	41.30	-3.26	10.82	-2.19	15.24	9.92	3.38	-1.74	27.05	-2.77	3.03	3.84
JPN	541.06	701.36	509.05	-14.69	-65.61	19.83	20.21	0.33	5.26	14.00	6.09	-2.96	-8.99	11.47	14.63	1.64	1.00
NLD	110.11	207.49	177.39	-63.56	-23.26	23.41	1.30	45.75	-8.53	11.89	2.07	6.45	2.12	51.18	9.49	13.33	2.30
NOR	27.15	48.74	47.36	-80.81	-16.23	30.19	-4.56	26.05	-11.80	29.48	8.46	8.39	0.26	41.11	17.79	25.12	3.24
ESP	94.10	229.38	148.46	-101.08	-23.10	54.44	-9.68	48.02	-6.16	18.86	7.66	16.05	-0.14	81.02	-6.41	26.45	2.54
SWE	44.18	62.53	70.93	-52.80	-28.44	18.02	-7.24	17.36	-16.11	9.45	24.59	4.91	22.69	37.35	10.94	7.26	6.99
CHE	71.51	108.30	105.12	-72.98	-13.65	20.90	14.50	21.38	6.36	15.77	-2.89	1.97	-1.24	40.05	-9.25	24.36	3.24
GBR	240.79	487.36	377.97	-52.09	-28.63	31.51	4.75	11.76	-3.06	27.06	-10.63	8.86	-3.00	66.02	10.22	9.27	7.91
USA	651.91	1741.89	1558.61	-125.53	-22.39	75.69	15.98	42.71	-12.49	41.23	19.58	-3.11	-17.75	104.44	0.29	31.76	6.25

Notes: Foreign CO_2 emissions for 1990, the peak years, and 2016. Changes from 1990 to the peak year, and from the peak year to 2016 are decomposed into the foreign carbon intensity (Q_f), intermediate demand source composition (C), total input structure (A^*), final demand source composition (F), final demand structure (B), final demand per capita (D), and population (P). Positive signs indicate increased emissions; negative signs represent decreased emissions.

Table B6 Detailed decomposition results for foreign carbon intensity, intermediate demand source composition, and final demand source composition.

		Decomposition (%)											
		Q_f				C				F			
		Q_f_low	Q_f_med	Q_f_high	Q_f_others	C_low	C_med	C_high	C_others	F_low	F_med	F_high	F_others
AUT	Pre.	-3.22	-11.15	-26.00	-5.57	5.96	14.58	-9.59	9.72	1.35	6.39	0.42	3.33
	Post.	-5.44	-4.02	-10.64	-13.47	4.02	-2.27	-6.06	1.03	0.53	1.36	-1.27	3.75
DNK	Pre.	-0.38	-5.47	-6.39	4.29	2.06	2.21	-3.39	-2.15	0.70	1.53	-0.06	0.48
	Post.	-9.49	-15.29	-32.29	-25.70	9.94	12.51	-10.14	15.40	0.93	2.93	-2.26	3.38
FIN	Pre.	-1.07	-8.25	-14.07	-53.78	3.46	9.04	27.24	3.42	0.79	3.71	-0.56	1.68
	Post.	-6.38	-9.20	-17.65	-19.75	5.18	2.11	-6.83	2.75	2.36	6.68	3.42	16.82
FRA	Pre.	-5.33	-10.51	-16.43	-13.75	7.13	13.07	-1.19	3.60	2.64	5.78	0.18	3.80
	Post.	-17.09	-10.82	-19.41	-23.57	6.80	10.16	-6.66	8.25	3.94	5.03	-2.35	5.37
DEU	Pre.	0.20	-1.65	0.37	-157.78	0.27	-2.69	44.75	-0.32	0.36	-0.35	-0.10	0.51
	Post.	-11.82	-18.00	-20.56	114.65	11.94	15.33	-54.25	14.50	3.12	5.04	-2.52	4.79
GRC	Pre.	-8.01	-16.74	-26.97	-40.29	22.39	21.43	12.78	10.83	5.84	9.80	2.74	6.86
	Post.	-8.18	-0.90	-5.93	-7.57	3.82	-4.28	-1.97	2.32	0.46	-1.00	-1.99	-0.02
ISL	Pre.	-3.78	-17.48	-39.67	-15.23	4.53	18.36	-4.34	9.02	1.85	12.36	6.63	5.76
	Post.	-2.84	-2.46	-8.35	-6.89	2.57	0.88	0.52	8.74	0.92	-1.18	-4.43	2.32
ITA	Pre.	-3.88	-13.37	-18.83	-12.56	9.33	21.71	0.46	9.79	2.97	6.09	1.49	4.69
	Post.	-8.79	-3.09	-9.54	-12.17	6.10	-9.50	-3.40	3.55	2.62	2.24	-0.41	5.48
JPN	Pre.	0.77	-8.23	-5.16	-2.08	1.84	11.28	11.40	-4.69	1.45	9.75	1.33	1.48
	Post.	-12.62	-25.27	-11.98	-15.75	11.30	2.92	-6.14	12.13	2.39	6.12	-2.88	0.46
NLD	Pre.	-5.66	-17.89	-23.70	-16.31	7.34	20.30	-11.73	7.49	2.32	6.35	-1.89	5.11
	Post.	-6.44	-2.61	-4.12	-10.08	4.77	-2.85	-1.98	1.37	0.56	0.67	-0.13	0.97
NOR	Pre.	-3.84	-19.29	-41.89	-15.80	5.45	13.58	2.30	8.87	2.64	10.21	8.31	8.31
	Post.	-3.94	-3.86	-2.89	-5.54	1.90	0.23	-8.43	1.75	1.56	3.65	-1.22	4.48
ESP	Pre.	-9.10	-22.14	-26.65	-43.18	12.56	25.13	12.29	4.45	4.04	10.91	-0.34	4.25
	Post.	-8.73	-0.69	-5.33	-8.35	2.44	-9.34	-3.72	0.94	3.28	2.23	-1.07	3.22
SWE	Pre.	-2.88	-10.53	-26.94	-12.46	4.59	13.29	-4.37	4.51	0.92	3.68	1.28	3.58
	Post.	-4.01	-2.89	-10.49	-11.06	2.43	-3.16	-8.80	2.29	1.51	4.09	6.14	12.85
CHE	Pre.	-2.53	-13.04	-43.75	-13.66	3.87	6.06	4.30	6.68	1.59	4.55	5.59	4.04
	Post.	-3.81	-2.35	-2.42	-5.07	3.83	2.85	-2.09	9.91	0.71	-2.10	-7.96	6.45
GBR	Pre.	-5.26	-16.55	-22.83	-7.45	7.20	17.87	-9.66	16.12	3.76	12.68	0.42	10.19
	Post.	-4.35	-5.30	-6.92	-12.06	2.61	0.53	-3.35	4.97	-0.70	-3.89	-5.06	-0.98
USA	Pre.	-9.92	-35.26	-19.32	-61.03	11.73	33.46	12.71	17.79	4.52	26.15	-1.98	12.54
	Post.	-4.45	-4.44	-3.81	-9.69	4.24	4.31	-2.30	9.74	1.75	0.48	0.27	17.08

Notes: Detailed decomposition results for foreign carbon intensity (Q_f), intermediate demand source composition (C), and final demand source composition (F) are presented. Q_f_low, Q_f_med, Q_f_high, and Q_f_others represent the contribution of foreign carbon intensity changes in low-, medium-, high-income, and other countries; C_low, C_med, C_high, and C_others represent the contribution to changes in intermediate demand sourcing shares from low-, medium-, high-income, and other countries; F_low, F_med, F_high, and F_others represent the contribution to changes in final demand sourcing shares from low-, medium-, high-income, and other countries.