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*Published in:*
Resources, Conservation and Recycling

*DOI:*
10.1016/j.resconrec.2020.105167

**IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.**

*Document Version*
Publisher's PDF, also known as Version of record

*Publication date:*
2021

Link to publication in University of Groningen/UMCG research database

*Citation for published version (APA):*
Dou, X., Deng, Z., Sun, T., Ke, P., Zhu, B., Shan, Y., & Liu, Z. (2021). Global and local carbon footprints of city of Hong Kong and Macao from 2000 to 2015. *Resources, Conservation and Recycling*, *164*, [105167]. https://doi.org/10.1016/j.resconrec.2020.105167

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Resources, Conservation & Recycling 164 (2021) 105167

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

# Global and local carbon footprints of city of Hong Kong and Macao from 2000 to 2015

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ARTICLE INFO

*Keywords:*
Carbon footprint
Three scopes emissions
Urban metabolism
Hong Kong
Macao

ABSTRACT

Hong Kong and Macao are featured with their urban metabolism as they heavily rely on the energy and resource supply from other regions. However, a comprehensive perspective is lacked to depict their $CO_2$ emissions due to the independence of statistical data. Here we analyze the carbon footprints of Hong Kong and Macao. The direct energy-related emissions (Scope 1), the emissions of cross-boundary electricity (Scope 2), and the embodied emissions associated with trade (Scope 3) are examined. Scope 1 carbon footprints of the two areas were stabilized at 50 Mt, accounting for 0.6% of those from Mainland China in 2018. Their global footprints were approximately three times of their Scope 1 emissions, accompanied by a continuous growth between 2000 and 2015, and the contribution of their local footprints has doubled on average. Their Scope 3 emissions were mainly due to the enormous unfavorable balance of trade. Meanwhile, the increasing impact of imports' higher emission intensity on their Scope 3 emissions should not be ignored. We suggest that Hong Kong and Macao should adjust their mitigation policies that focus only on Scope 1 emissions as developed cities outsourcing production through supply chains.

## 1. Introduction

The most impact of human activities on the climate mainly comes from the increasing greenhouse gas (GHG) emissions (Jiang et al., 2019), while carbon dioxide ($CO_2$) is the most common GHG of global warming at present. Covering only 2% of the Earth's surface, the cities contribute 75% of the global carbon emissions (Grimm et al., 2008; IPCC, 2006) and have become the key areas for global climate mitigation. Understanding the characteristics of cities' carbon flow will help formulate wise mitigation policies to better control cities' emissions (Zhao et al., 2017). Urban metabolism is a comprehensive method first proposed by Wolman in 1965. It regards the urban complex system as organic life and analyzes the flow of material and energy between the city and its surroundings at multi-levels and multi-scales (Pincetl et al., 2012; Wolman, 1965). In the context of globalization and regional economic integration, the flow of materials and energy has become more frequent and distant (Agostinho and Pereira, 2013; Folke et al., 1997). Thus, the boundary of a city's carrying area has been extended even to the whole world, especially in some externally oriented cities. After the concept of urban metabolism was proposed, many scholars have developed various methods to analyze the energy and material flows related to the production and consumption of human activities (Beloin-Saint-Pierre et al., 2017; Chen and Chen, 2015; Chen et al., 2020). Among these flows, "Carbon Footprint" represents one of the most important flows between a city and worldwide consequences. It is defined as the measure of the exclusive total amount of $CO_2$ emissions that are directly and indirectly caused by an activity or is accumulated over the life stages of a product. The "Carbon Footprint" is conducive to tracking carbon flow coming into, being added to the stocks of, and eventually leaving the city (Wiedmann and Minx, 2008). In recent years, the "Carbon Footprint" has been applied and promoted internationally. For example, Chambers et al. (2007) quantified hurricane Katrina's carbon footprint on U.S. Gulf Coast forest. Song et al. (2016) calculated the carbon footprint of a publication with both direct and indirect emissions covered. Mancini et al. (2016) increased the clarity and transparency of the ecological footprint by applying the rationale and methodology behind the carbon footprint component. Zhang et al. (2016) proposed a methodology to study the observed urbanization effects on carbon footprint. Chavez and Ramaswami (2013) compared the policy relevance and derived mathematical relationships between Carbon Footprints and Purely-Geographic Inventory accounting approaches.

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https://doi.org/10.1016/j.resconrec.2020.105167
Received 29 May 2020; Received in revised form 2 August 2020; Accepted 14 September 2020

Hong Kong and Macao are among the most developed cities in China and most densely populated cities in the world with a population of 7483 thousand and 672 thousand living in an area of 1106 $km^2$ and 33 $km^2$ respectively. The two cities are the most important trade zones in the global economy because of their special roles as gateway cities between Mainland China and the rest of the world. In addition to direct emissions from anthropogenic activities within the cities, the indirect emissions embodied in cross-boundary electricity and international trade should not be neglected. It has been recognized as the more valuable choice to inform decision-makers about both direct and indirect carbon emissions of the urban areas (Lombardi et al., 2017).

The carbon footprint research for Hong Kong and Macao could not only improve our understanding of cities' complete carbon flows but also provide more sensible insights into promoting sustainable development paths. A clear definition of different scopes of urban emissions is needed to avoid misestimation and double-counting in the emission accounting process. Initiatives such as the Greenhouse Gas Protocol and International Council of Local Environmental Initiatives (ICLEI) suggested 3 scopes of urban emission boundary, in which Scope 1, 2, and 3 emissions include direct emissions within the territory boundary caused by the direct use of fossil energy through industrial activities, the emissions from the consumption of electricity purchased from upstream power plants (defined as "carbon footprint from cross-boundary electricity" thereafter), and the emissions from upstream production through the supply chain due to the consumption of products (carbon footprint from trade), respectively(Kennedy et al., 2010, 2011; Liu et al., 2012). Local governments and some international research institutes such as the British Petroleum (British Petroleum Company, 2019), Emissions Database for Global Atmospheric Research (Crippa et al., 2019), Carbon Dioxide Information Analysis center (Gilfillan et al., 2019), and International Energy Agency (International Energy Agency, 2019) have published Scope 1 emissions data for Hong Kong and Macao. Some studies contributed to reporting embodied $CO_2$ emissions in Hong Kong and Macao(Chen et al., 2017; Huang et al., 2019). Yet the research is needed to conduct the complete measurement of the carbon footprint for these two cities, as two cities play an important role in connecting Mainland China and the world through the trade. This study fills such a gap by analyzing three scopes emissions of Hong Kong and Macao under the framework of carbon footprint, which could provide data support for emissions reduction policy-making in gateway cities.

Here we investigate the direct $CO_2$ emissions in Hong Kong and Macao by sectors and fuel types based on the Reference Approach and Sectoral Approach (Scope 1), the indirect emissions of cross-boundary electricity (Scope 2), and the embodied emissions associated with trade (Scope 3) using the Multi-Regional Input-Output Model (MRIO), from 2000 to 2015. The most up-to-date database and the latest emission factors (Liu et al., 2015) are applied in this study to obtain the best estimates. Based on our new data, we decompose the main drivers of carbon footprints embodied in trade, to provide a theoretical basis for the authorities to formulate appropriate mitigation policies.

## 2. Materials and methods

We constructed a comprehensive framework of this study to systematically summarizes the relationship and significance of the three components of carbon footprints and show the role of index decomposition analysis (**Fig. 1**).

### 2.1. Scope 1 emissions accounting

The Reference Approach recommended by the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories can be used to estimate the Scope 1 $CO_2$ emissions. The Reference Approach requires statistical data on fuel production, import, export, and changes in stocks. It also requires limited data on fuel consumption for non-energy uses, where carbon may need to be removed. We calculate the Reference Approach $CO_2$ emissions according to Eq. (1).

$$CE_{ref-i} = AD_{ref-i} \times EF_i \times M \tag{1}$$

where $CE_{ref-i}$ refers to the reference $CO_2$ emissions from fossil fuel *i*, $EF_i$ and $AD_{ref-i}$ are the emission factors and apparent consumption (TJ) of the corresponding fossil fuel *i*, respectively, and *M* is the molecular weight ratio of carbon dioxide to carbon (44/12). The emission factors are the carbon content, which is the $CO_2$ emissions per net caloric value produced by fossil fuel, and the oxidation rate of fossil fuel, which refers to the oxidation ratio during fossil fuel combustion. Values of $AD_{ref-i}$ are calculated as in Eq. (2). The non-energy use and loss parts should be removed from the fuel's apparent consumption as these two parts don't generate $CO_2$ emission.

$$\begin{aligned} AD_{ref-i} = {} & Indigenous\ Production + Imports - Exports \pm Stock\ Change \\ & - Non - Energy\ Use - Loss \end{aligned} \tag{2}$$

Related fossil fuels considered for computation and emission factors are presented in **Table 1**. According to our previous survey of China's fossil fuel quality and cement process, the IPCC emission factors are approximately 40% higher than China's survey value (Liu et al., 2015). Therefore, here we use updated emission factors.

Besides, according to the IPCC guidelines (IPCC, 2006), we also adopt the Sectoral Approach to calculate emissions based on the fossil fuels' sectoral combustion; see Eq. (3) below.

$$CE_{ij} = AD_{ij} \times EF_i \times M \tag{3}$$

where $CE_{ij}$ refers to the $CO_2$ emissions from fossil fuel *i* burned in sector *j;* $AD_{ij}$ represents the fossil fuel consumption by the corresponding fossil fuel types and sectors; the emission factors for the fossil fuels in Eq. (3) are the same as those used in the Reference Approach.

The sectoral energy final use data mainly come from statistical yearbooks. However, for Hong Kong where the quality of such data is low, we combine the Energy End-use Data provided by Hong Kong Electrical and Mechanical Services Department to further improve and supplement the statistical yearbook data, which can be downloaded free online. According to the sector classification of available statistic data, we finally consider *Industry, Commerce, Local consumption*, and *Thermal power* for sectoral approach emissions of Hong Kong and *Industry, Construction, Transportation, Commerce, Local consumption, Thermal power*, and *Other sectors* for sectoral approach emissions of Macao.

### 2.2. Scope 2 emissions accounting

The "carbon footprint" could track carbon emissions outside the boundary of a city. Carbon footprints from cross-boundary electricity (Scope 2 footprint) are calculated as follows.

The emission factors (EFs) of electricity generation will change greatly with time due to the different technology levels and energy structure in different years. Hong Kong has imported electricity from the Daya Bay nuclear power station through South China Grid, which does not generate $CO_2$ emissions. Therefore, this part of emission in Hong Kong is not included. Macao has imported power from Guangdong Province through South China Grid. Here we use the following Eq. (4) to calculate the emission factor of electricity for South China Grid:

$$EF_s = \sum \frac{E_k}{G_k} \tag{4}$$

where $EF_s$ represents the *EF* of electricity for South China gird, *k* is the province which the state grid served. $E_k$ is the total $CO_2$ emission from fossil fuel burned in the *Thermal power* sector from *k* province. $G_k$ is the total electricity supply from *k* province, which contains the electricity

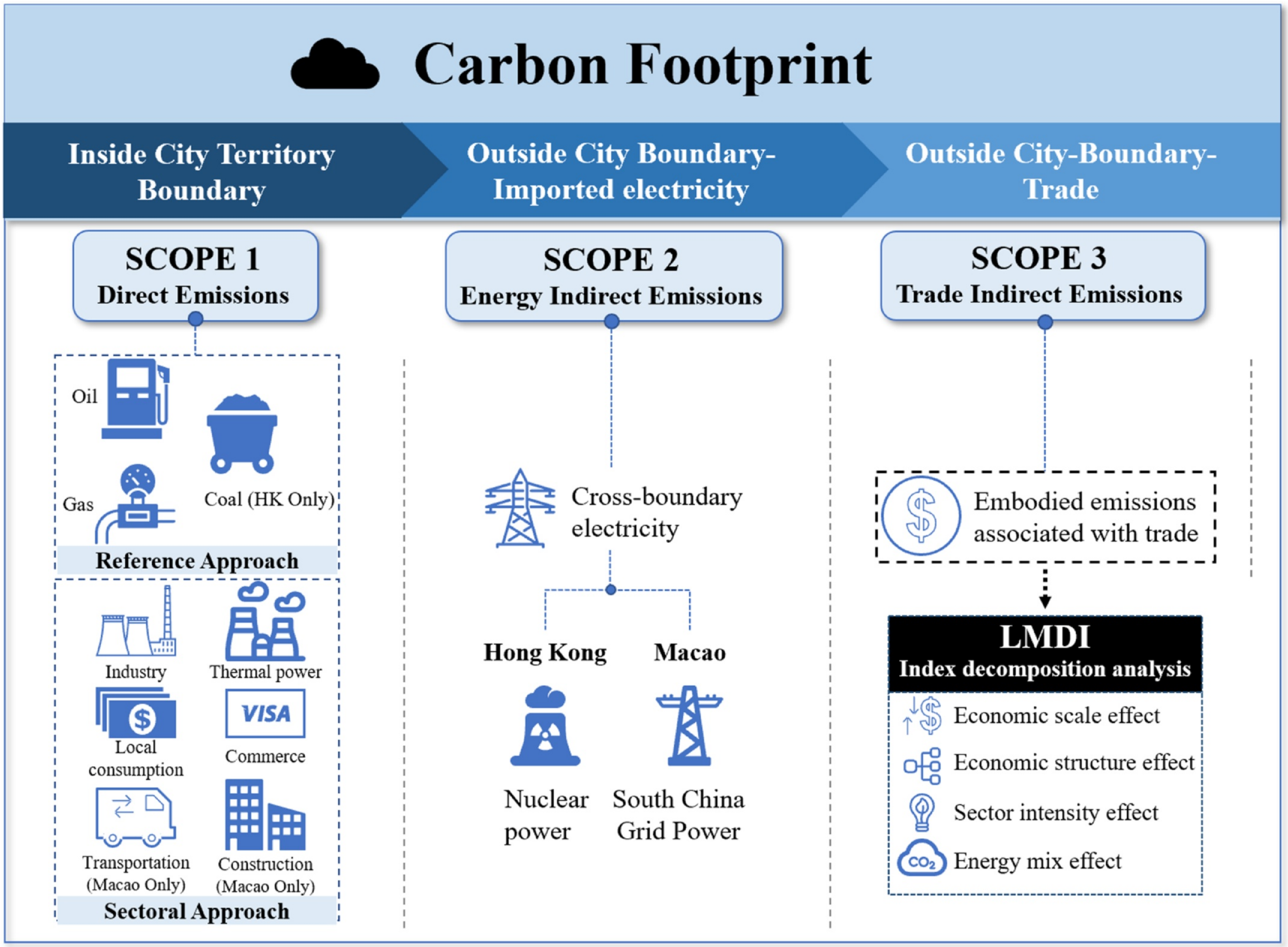

**Fig. 1.** The framework of methods.

**Table 1**
Fossil Fuels and Emission Factors (*Carbon Content*).

| | Fuels | Carbon Content (tonneC/TJ) |
|---|---|---|
| Hong Kong | Coal Products | 26.32 |
| | Oil Products | 20.08 |
| | Natural Gas | 15.32 |
| Macao | Gasoline | 18.90 |
| | Kerosene | 19.60 |
| | Gas oil & diesel | 20.20 |
| | Fuel oil | 21.10 |
| | Liquefied petroleum gas | 20.00 |
| | Natural gas | 15.32 |

Data source: (Liu et al., 2015).

**Table 2**
$CO_2$ Emission Factors on Power Generation of South China Grid from 2000 to 2018(ton $CO_2$/TJ).
Source: (Liu et al., 2012).

| Year | Emission factor | Year | Emission factor |
|---|---|---|---|
| 2000 | 189.44[a] | 2010 | 178.50[b] |
| 2001 | 194.72[a] | 2011 | 181.01[b] |
| 2002 | 196.11[a] | 2012 | 160.71[b] |
| 2003 | 210.28[a] | 2013 | 156.55[b] |
| 2004 | 220.00[a] | 2014 | 130.82[b] |
| 2005 | 203.06[a] | 2015 | 119.39[b] |
| 2006 | 203.61[a] | 2016 | 116.94[b] |
| 2007 | 201.39[a] | 2017 | 116.94[b] |
| 2008 | 180.28[a] | 2018 | 116.94[b] |
| 2009 | 171.11[a] | | |

[a] Source: (Liu et al., 2012).
[b] Data Source: authors' calculation.

from the power plant, renewable energy, and unclear power sources. Values of $E_k$ are calculated as in Eq. (5).

$$E_k = \sum_i AD_{ik} \times EF_i \times M \tag{5}$$

where $AD_{ik}$ represents the fossil fuel $i$ consumption burned for electricity production; $EF_i$ is the emission factors for the fossil fuel $i$, including the net calorific value, which is the heat value produced per physical unit of fossil fuel combustion, the carbon content, and the oxidation rate. Net calorific value is also referred to our previous research (Liu et al., 2015).

The emission factors of electricity for the South China grid are calculated by adopting data from the Chinese Electricity Statistics Yearbook and China Energy Statistical Yearbook, and results are presented in Table 2. Due to data limitations, the emission factors are assumed to be constant during 2016–2018.

### 2.3. *Scope 3 emissions accounting*

Scope 3 emissions are equal to emissions embodied in exports minus emissions embodied in imports. To calculate Scope 3 emissions, the

**Table 3**
Sector categories.

| Sectors in this study | Sectors in the Eora database |
|---|---|
| Electricity and heat production | Electricity, Gas, and Water |
| Other energy industry own use | Mining and Quarrying |
| Manufacturing industries and construction | Textiles and Wearing Apparel |
| | Wood and Paper |
| | Petroleum, Chemical, and Non-Metallic Mineral Products |
| | Metal Products |
| | Electrical and Machinery |
| | Transport Equipment |
| | Other Manufacturing |
| | Recycling |
| | Construction |
| Transport | Transport |
| | Post and Telecommunications |
| Residential | Private Households |
| Commercial and public services | Food & Beverages |
| | Maintenance and Repair |
| | Wholesale Trade |
| | Retail Trade |
| | Hotels and Restaurants |
| | Financial Intermediation and Business Activities |
| | Public Administration |
| | Education, Health and Other Services |
| Agriculture/forestry | Agriculture |
| Fishing | Fishing |
| Final consumption not elsewhere specified | Others |
| | *Re*-export & *Re*-import |

MRIO model should be adopted to track emissions embodied in imports and exports (Duchin, 1992; Hertwich and Peters, 2009; Peters and Hertwich, 2008; Shui and Harriss, 2006). Here we adopt the Eora database, which is a global MRIO database at high country and sector resolution distinguishing 189 countries represented by 26 sectors (Lenzen et al., 2012, 2013).

An MRIO table assumes that an economy consists of $G$ regions and $n$ sectors. The total output of a region is used at home and abroad by the consumption of intermediate or final products. This basic relationship between gross output, intermediate goods, and final demand goods is expressed below:

$$X = AX + Y \tag{6}$$

Where $X$ represents the total output matrix. $A$ represents the matrix of input-output coefficients, and therefore $AXE$ represents the matrix of intermediate demand (the $T$ matrix in Eora). Finally, $Y$ represents the matrix of final demand (the $FD$ matrix in Eora).

By solving $X$, we have

$$B = (I - A)^{-1} \tag{7}$$

Where $B$ is the Leontief inverse matrix. $I$ is the identity matrix.

Let $C$ represents a vector of sectoral $CO_2$ emission coefficients, in which each element represents the emitted $CO_2$ emissions for producing one unit of total output:

$$C = [C_1\ C_2 \ldots\ C_n] \tag{8}$$

Eq. (9) and Eq. (10) are modified to calculate the emissions embodied in imports and exports of region $s$, respectively:

$$CO_2{}^{import} = diag(C_{\sim s})Bdiag(Y^{\cdot s}) \tag{9}$$

$$CO_2{}^{export} = diag(C_s)Bdiag(Y^{s\cdot}) \tag{10}$$

Where $CO_2{}^{import}$ ($CO_2{}^{export}$) represents the total embodied emissions in import(export) of region $s$; $C_{\sim s}$ represents a vector of sectoral $CO_2$ emission coefficients for all other regions but with zeros for the emission coefficients of region $s$; $C_s$ represents a vector of sectoral $CO_2$ emission coefficients for the region $s$ but with zero for the emission coefficients of other regions. $Y^{\cdot s}$ is the final demand vector of region $s$. $Y^{s\cdot}$ is the final demand vector of the total sectoral final demand of other regions but excluding the final demand of region $s$. As the environmentally extended data provided by Eora is not accurate, we revised $CO_2$ emissions data based on our calculated emissions for Hong Kong and Macao, and the International Energy Agency (IEA) for the others, which published sectoral fossil $CO_2$ emissions of all world countries. **Table 3** shows how to merge sectors of the Eora database into the sector categories adopted in this study.

### 2.4. Index decomposition analysis

The Logarithmic Mean Divisa Index(LMDI) decomposition method was proposed to solve different decomposition problems in 1998 (Ang et al., 1998). Here, LMDI is adopted to perform the residual-free decomposition of the factors affecting Scope 3 emissions. The expression is shown as Eq. (11) (Ang, 2009):

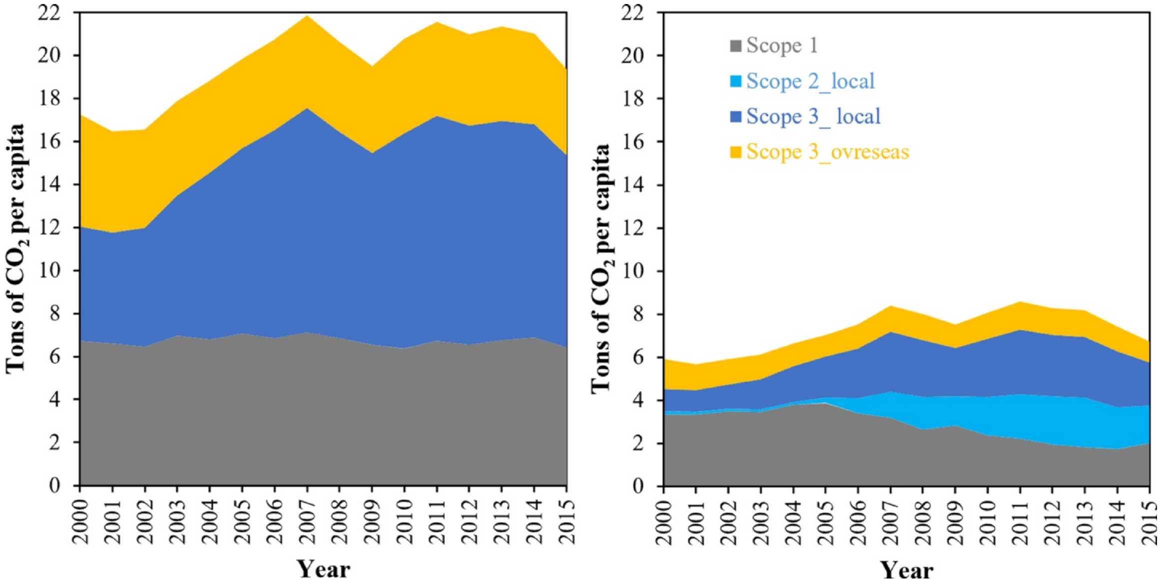

**Fig. 2.** Carbon footprints per capita of Hong Kong (a) and Macao (b) (2000–2015). Note: carbon footprints per capita of Hong Kong and Macao are based on results in this study and population data taken from the World Bank(The World Bank, 2020).

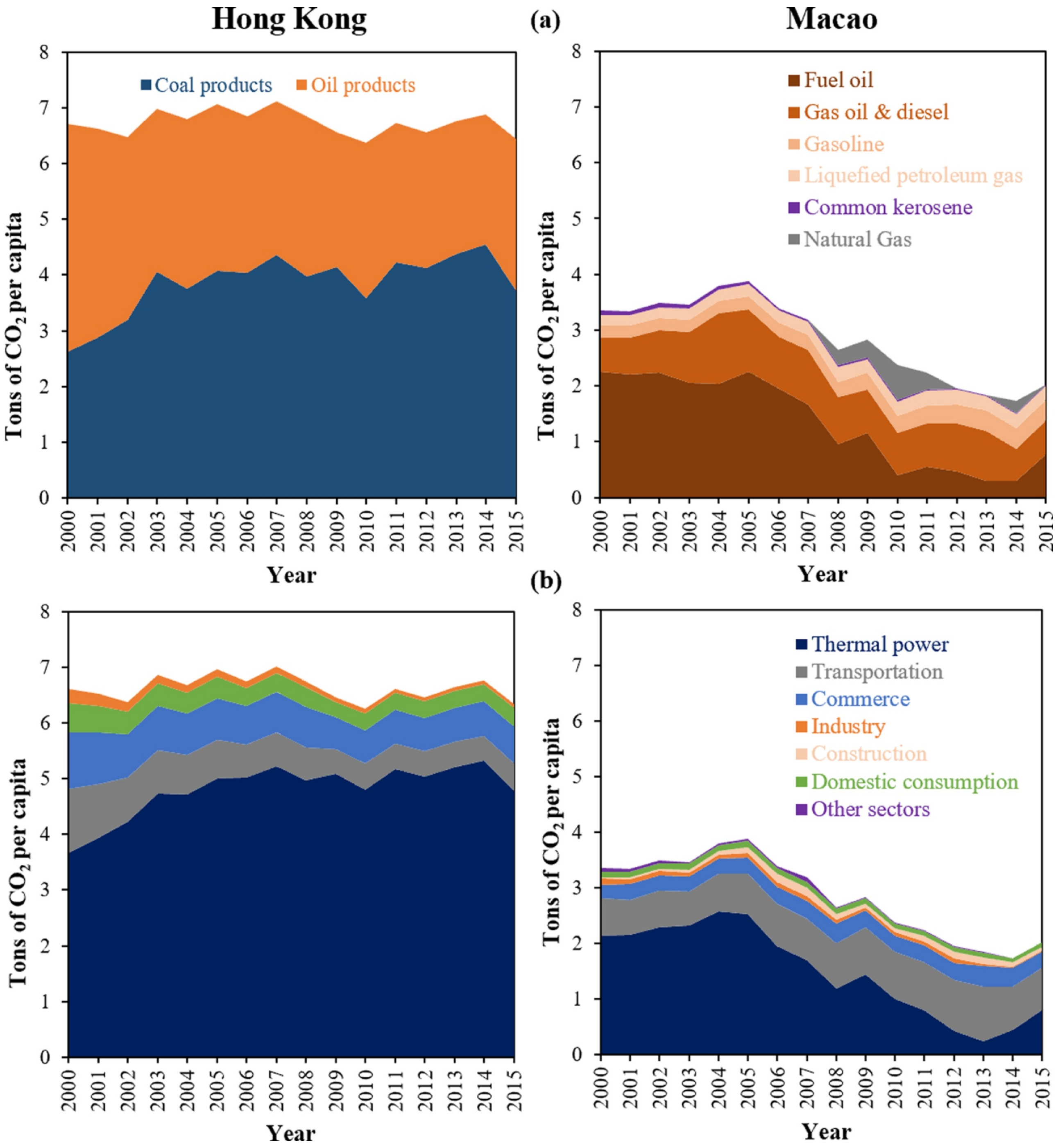

**Fig. 3.** Per capita Scope 1 emissions of various energy types (a) and from different sectors (b) in Hong Kong and Macao.

$$E = \sum_i E_i = \sum_i Q\frac{Q^i}{Q}\frac{V^i}{Q^i}\frac{E^i}{V^i} = \sum_i QS_iI_iF_i \tag{11}$$

Where $E$ represents Scope 3 emissions, $Q$ is the GDP value of imports or exports, $S_i$ is the share of the GDP value for sector $i$, $I_i$ is the energy intensity of sector $i$, and $F_i$ is the emission per unit of energy consumption of sector $i$. We use the additive form decomposition method and it can be expressed as Eq. (12).

$$\Delta E = E^{import} - E^{export} = \Delta E_{act} + \Delta E_{str} + \Delta E_{int} + \Delta E_{mix} \tag{12}$$

Where $\Delta E$ is the difference between the $CO_2$ emissions embodied imports ($E^{import}$) and the $CO_2$ emissions embodied in exports ($E^{export}$). Four factors are considered in this study: (1) economic scale effect(the difference in the total economic value of imports and exports); (2) economic structure effect(the sector responsible for imports and exports); (3) sector intensity effect(the difference in sectoral energy intensity between the imports and exports); and (4) energy mix effect (carbon intensity of energy used to produce imports and exports). $\Delta E_{act}$, $\Delta E_{str}$, $\Delta E_{int}$ and $\Delta E_{mix}$ represent economic scale effect, economic structure effect, sector intensity effect, and energy mix effect, respectively.

$$\Delta E_{act} = \sum_i w_i \ln\left(\frac{Q_i^t}{Q_i^0}\right)$$

$$\Delta E_{str} = \sum_i w_i \ln\left(\frac{S_i^t}{S_i^0}\right)$$

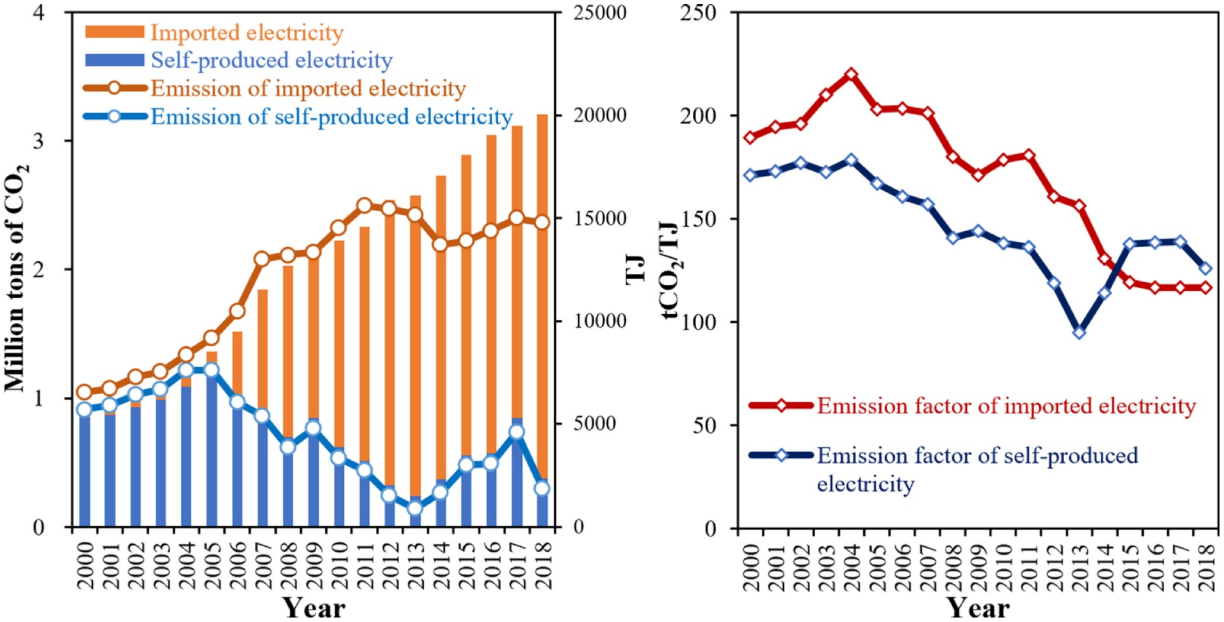

**Fig. 4.** The comparison of self-produced electricity and imported electricity in Macao (2000–2018).

$$\Delta E_{int} = \sum_i w_i \ln\left(\frac{I_i^t}{I_i^0}\right)$$

$$\Delta E_{mix} = \sum_i w_i \ln\left(\frac{F_i^t}{F_i^0}\right)$$

$$w_i = \frac{E_i^t - E_i^0}{\ln E_i^t - \ln E_i^0} \tag{13}$$

Where $Q^t$, $S^t$, $I^t$ and $F^t$ is the GDP, GDP share, energy intensity, and the emission coefficient of imports, respectively. $Q^0$, $S^0$, $I^0$ and $F^0$ is the GDP, GDP share, energy intensity, and the emission coefficient of exports, respectively.

## 3. Results

### 3.1. The overall trend in carbon footprints

Fig. 2 describes the trends of per capita carbon footprints in Hong Kong and Macao between 2000 and 2015. According to whether their trade partner is Mainland China, we divide Scope 3 emissions into Scope 3_ local (Mainland China) and Scope 3_ overseas (the rest of the world), as shown in Fig. 2. Their global carbon footprints showed a rapid growth until reaching the historical peaks at 22 t per capita and 8 t per capita in 2007, respectively, and then have controlled a high level till 2008 when they both showed a significant decrease mainly due to the global financial crisis. In 2015, the global carbon footprints were approximately 3 times the Scope 1 emissions in Hong Kong and Macao. Overall, the global carbon footprint changes in Hong Kong and Macao were similar. Although Macao's Scope 1 emissions dropped significantly during this period, the increase in its Scope 2 emissions effectively offset the decline in Scope 1 emissions. Since 2007, their global carbon footprints have remained at a high level.

Considering Hong Kong and Macao's heavy special reliance on the supply from Mainland China, the local carbon footprint for Mainland China (Scope 3_local plus Scope 2_local) and overseas carbon footprint for the other regions (Scope 3_overseas) are discussed separately in this study. Local carbon footprint played an increasingly critical role, while Scope 1 emissions and overseas carbon footprint both declined or kept stable from 2000 to 2015. In detail, Hong Kong's local carbon footprint per capita increased from 31% to 46% of the global carbon footprint per capita during this period, while overseas carbon footprint and Scope 1 emissions always stabilized at around 4 t per capita and 7 t per capita during this period respectively. In terms of Macao, local carbon footprint accounted for 56% of global carbon footprint in 2015, which was approximately three times of that proportion in 2000(20%), while overseas carbon footprint kept stable at around 1 t per capita and Scope 1 emission even continued to decline from 4 t per capita in 2005 to 2 t per capita in 2015 after peaking in 2005.

### 3.2. Features and trajectories of Scope 1 emissions

We show Scope 1 emissions of various energy types and from different sectors in Hong Kong and Macao in Fig. 3. They have slightly flattened or even decreased in recent years. In 2018, Hong Kong (47.1 Mt) and Macao (3.1 Mt) emitted a total of approximately 50 Mt of $CO_2$, accounting for approximately 0.6% of the direct emission in Mainland China(British Petroleum Company, 2019). As Fig. 3**(a)** shown, clearly coal products contributed most of the emissions in Hong Kong while oil products contributed most to Macao. Fig. 3**(b)** shows that the thermal power sector, transportation sector, and commerce sector were the main contributors to $CO_2$ emissions in Hong Kong and Macao, but with different rankings. Particularly, emissions emitted by the thermal power sector in Macao significantly dropped to 0.8 t per capita in 2015, less than half of those in 2000(2.1 t per capita). The differences in the trends of Scope 1 emissions between Hong Kong and Macao were mainly due to the sharp decline of fuel oil combustion and the significant reduction of fossil fuel combustion in the thermal power sector in Macao.

### 3.3. Macao's Scope 2 emissions

We also calculate the carbon footprint from the cross-boundary electricity of Macao. It is noted that this part of emission in Hong Kong is zero because of the clean nature of imported nuclear power. Fig. 4 shows the comparison of self-produced electricity and imported electricity in Macao. To satisfy the growing power demand, Macao has imported more electricity from the South China Grid of Mainland China to meet the mounting demand of consumers (Fig. 4(a)). In the past two decades, the proportion of imported electricity in Macao's total power consumption has increased significantly and has surpassed electricity generation from local thermal power plants since 2007. Macao's $CO_2$

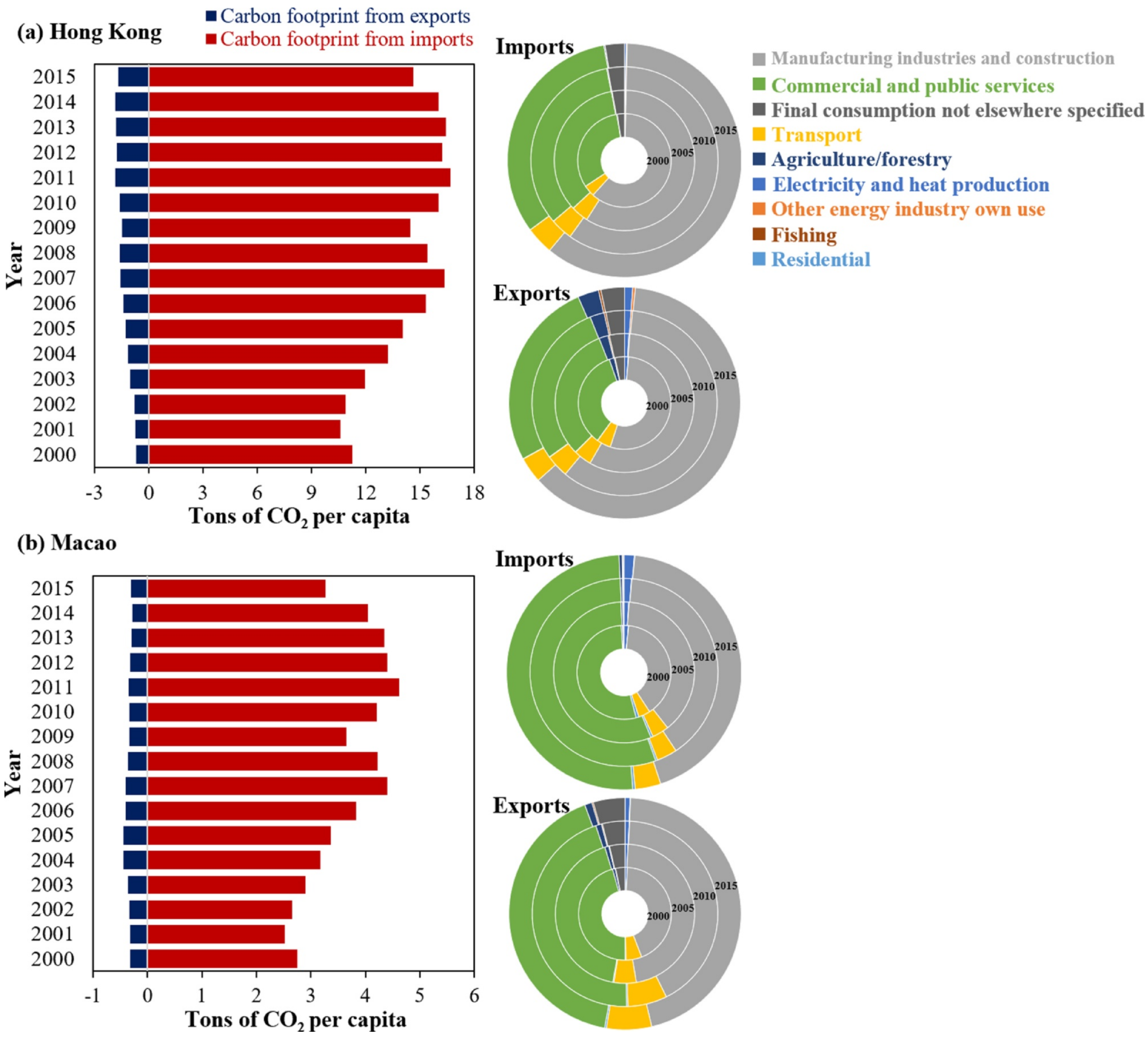

**Fig. 5.** Per capita Scope 3 emissions and their sectoral contribution in Hong Kong (a) and Macao (b) (2000–2015).

emissions emitted by electricity consumption peaked in 2011. Since then, Macao's total emissions caused by electricity consumption have shown a slight downward trend with the imported electricity from Mainland China playing an increasingly important role. Fig. 4(b) shows that since 2015, the emission factor of cross-boundary electricity has been smaller than that of local electricity in Macao. It indicates that imported electricity has been less carbon-intensive than self-produced electricity in Macao.

### 3.4. Features and sources of Scope 3 emissions

Fig. 5 shows the trend of Scope 3 emissions per capita in Hong Kong and Macao, where they varied from 10 t to 15 t and from 2 t to 4 t in Hong Kong and Macao, respectively. Their per capita Scope 3 emissions from imports increased from 2001 to 2007 and then decreased due to the global financial crisis in 2008 and 2009. Since then, they began to soar again, reaching historical peaks in 2011. The Scope 3 emissions from exports in Hong Kong was on the rise between 2000 and 2015, but it declined significantly in 2009. In Macao, it first increased slightly from 2000 to 2005, and then fell sharply for a long time, before stagnating between 2011 and 2015. The main factor leading to the change in Hong Kong's per capita Scope 3 emissions from exports is that Hong Kong, as a global financial and trade center, was significantly affected by the decline in global business confidence caused by the global financial crisis in 2009. While the main driver of this kind of trend in Macao is that, since 2005, the abolition of Macao's export quotas in international garment trade by WTO has formally come into forces, so that export-oriented apparel manufacturing is inevitably in recession (Tang and Sheng, 2009).

Fig. 5 also shows the sectoral contribution of Hong Kong and Macao's Scope 3 emissions over time. We classified nine sectors here and the composition details of each sector are shown in Table 3. *Manufacturing Industries and Construction* (*MIC*) is the largest contributor to Hong Kong's Scope 3 emission from imports, accounting for approximately 60% of its Scope 3 emission from imports annually. *Commerce and Public Services* (*CPS*) is the second-largest contributor, accounting for approximately 33% annually. While for Macao, *CPS* is the largest contributor, accounting for around 54% annually, and *MIC* is the second-largest contributor, accounting for approximately 40% annually. During the period 2000–2015, the shares of Scope 3 emission from imports contributed by these two leading sectors in Hong Kong and Macao were relatively stable, generally fluctuating within the

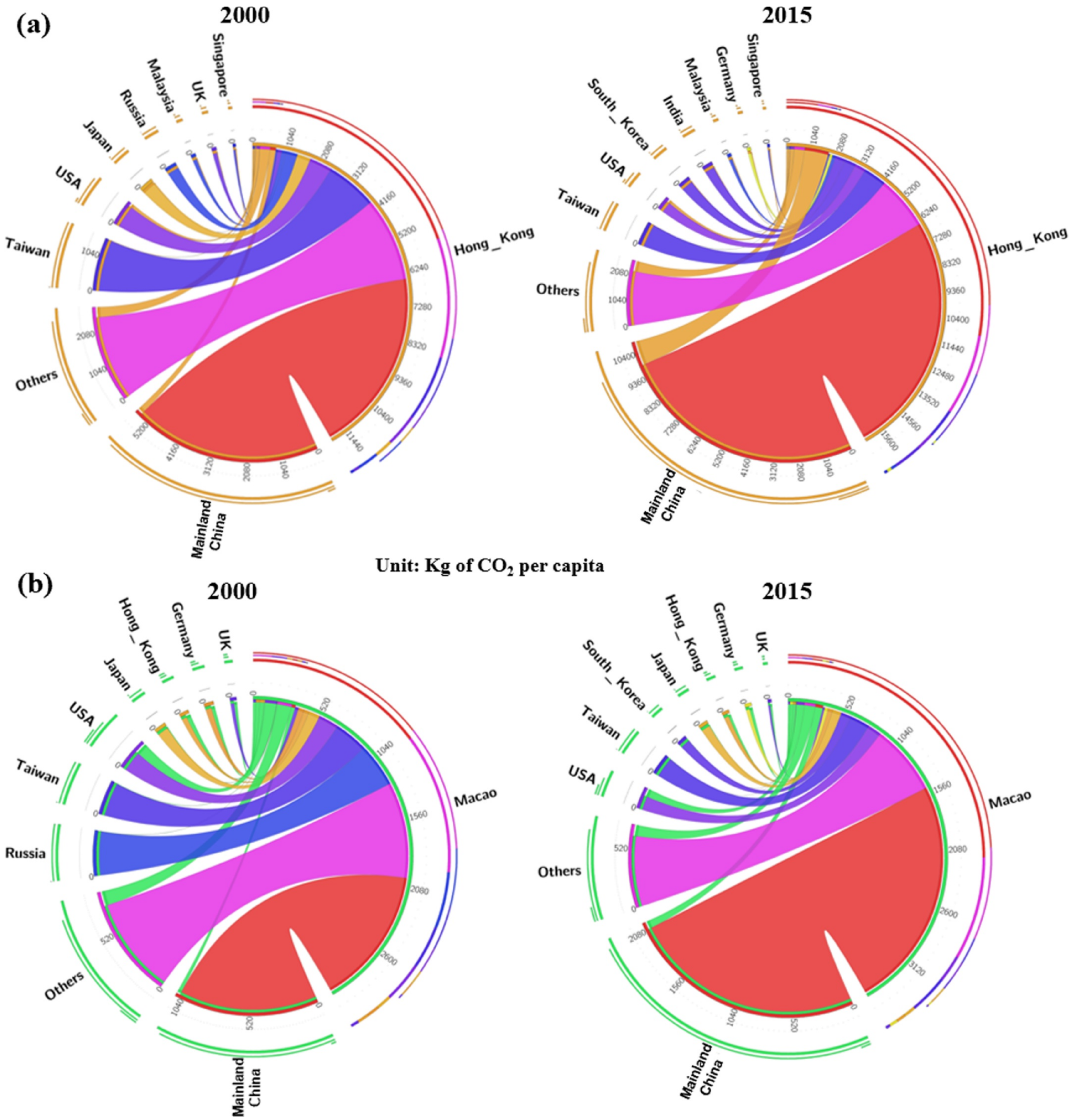

**Fig. 6.** The flows of per capita Scope 3 emissions of Hong Kong (a) or Macao (b) in 2000(left ones) and 2015(right ones). NOTE: We have used the software Circos for performing this Figure (Krzywinski et al., 2009). The Circos visualizes the flows of emissions by representing a region's outflow and inflow as segments along the inner circle, in which the ribbons touch the outflowing regions, but terminate a short distance before reaching the inflowing regions. By adding a scale and tick marks, it's easy to precisely determine the thickness of the ribbons, i.e., the flowing values. The outer circle draws the compositions of a region's inflow, outflow and total flow.

range of 92% to 93% and 92% to 94% respectively. MIC's huge contribution to Scope 3 emissions is mainly due to the high emission intensity of trans-boundary utilities, manufacturing, and transport & storage sectors(Hung et al., 2019). And the huge contribution of CPS is mainly attributed to the expansion of the consumption demand scale, especially the consumption of Hong Kong's developed commerce and service dominated by financial services and trade and Macao's developed gaming-led tourism service(Wang et al., 2019). Compared with Hong Kong, Macao is also a fast-growing city, but the fact that its *CPS* has contributed more than its *MIC* reveals Macao's over-reliance on the gaming industry and its shrinking manufacturing industry.

We also show the sectoral contribution of Hong Kong and Macao's Scope 3 emissions from exports over time in **Fig. 5**. Just like *MIC* and *CPS* contributed most to the Scope 3 emissions from imports, these two sectors also dominated the Scope 3 emissions from exports. Differently, for Macao, in terms of the Scope 3 emissions from imports, the

**Table 4**
Top 5 Regions for Per Capita Scope 3 Emissions from Imports and Exports in Hong Kong and Macao (Tons of $CO_2$ per capita).

| No. | | Imports in 2000 | | Imports in 2015 | | Exports in 2000 | | Exports in 2015 | |
|---|---|---|---|---|---|---|---|---|---|
| **1** | **Hong Kong** | China | 5.48 | China | 9.88 | China | 0.17 | China | 0.98 |
| **2** | | Taiwan | 1.54 | Taiwan | 0.95 | USA | 0.10 | USA | 0.12 |
| **3** | | USA | 0.67 | South Korea | 0.47 | Singapore | 0.03 | Singapore | 0.05 |
| **4** | | Japan | 0.40 | USA | 0.44 | UK | 0.03 | Malaysia | 0.04 |
| **5** | | Russia | 0.35 | India | 0.40 | Malaysia | 0.03 | Germany | 0.03 |
| | | Others | 2.81 | Others | 2.50 | Others | 0.34 | Others | 0.49 |
| | | **Total** | **11.25** | **Total** | **14.63** | **Total** | **0.70** | **Total** | **1.71** |
| **1** | **Macao** | China | 1.06 | China | 2.08 | USA | 0.09 | USA | 0.07 |
| **2** | | Russia | 0.34 | Taiwan | 0.18 | Hong Kong | 0.03 | China | 0.07 |
| **3** | | Taiwan | 0.26 | USA | 0.12 | Germany | 0.03 | Germany | 0.03 |
| **4** | | USA | 0.16 | South Korea | 0.09 | China | 0.03 | Hong Kong | 0.02 |
| **5** | | Japan | 0.08 | Japan | 0.08 | UK | 0.02 | UK | 0.02 |
| | | Others | 0.85 | Others | 0.72 | Others | 0.12 | Others | 0.11 |
| | | **Total** | **2.75** | **Total** | **3.27** | **Total** | **0.32** | **Total** | **0.31** |

contribution share of *CPS* was approximately 14% higher than that of *MIC*, while in terms of the Scope 3 emissions from export, that of these two sectors were almost the same, accounting for approximately 44%. The main reason for this difference is that the ultra-high-speed development of Macao's gaming industry has promoted the development of Macao's import industry, but it has not contributed much to its export industry.

We show the flows of per capita Scope 3 emissions between Hong Kong and Macao and their main trading partners in 2000 and 2015 at the regional level in Fig. 6. Here we present the top five contributing partners under corresponding situations, and the remaining partners are merged into 'others'. Table 4 reports the detailed flowing values of them. Hong Kong and Macao are typical net importers of emissions due to their heavy reliance on imports from other regions. We show that the contribution from Mainland China as the leading contributor to their per capita Scope 3 emissions from imports doubled from 5.48 t and 1.06 t in 2000 to 9.88 t and 2.08 t in 2015 for Hong Kong and Macao, respectively.

In general, the main bearers of carbon footprints from trade are also the main imposers. Mainland China's leading contribution to Hong Kong's Scope 3 emissions from exports has grown significantly from 0.17 t per capita in 2000 to 0.98 t per capita in 2015, and the difference between the contribution of USA as the second contributor has become increasingly significant. And for Macao, although China has not exceeded the USA to become the leading contributor, its contribution has increased from 0.03 t per capita as the fourth place in 2000 to 0.07 t per capita as the second place in 2015, while the contribution of the USA declined during the same period. If such a normal growth rate is upheld, Mainland China will soon beat the USA to be the leading contributor.

### 3.5. *Effects of driving factors on changes in Scope 3 emissions*

Hong Kong and Macao are the most important trade zones in the global economy as gateway cities between Mainland China and the rest of the world. It is confirmed by our research that the Scope 3 emissions contributed the most to their global carbon footprints among the three scopes due to their much more frequent import and export activities (Fig. 2). Therefore, we analyze the driving factors of Scope 3 emissions in Hong Kong and Macao to provide a basis for how to implement mitigation policies for this leading part of the global footprint (Fig. 1). A time serial LMDI decomposition analysis is effectively adopted to explore the relationships between Scope 3 emissions and economic scale effect, economic structure effect, sector intensity effect, and energy mix effect. Fig. 7 shows the contributions of the different factors to the per capita Scope 3 emissions of Hong Kong and Macao. Black bars show the effect of the economic scale, orange bars show the effect of economic structure, and purple bars show the effect of emissions intensity (the combination of the energy mix and sector intensity). Scope 3 emissions (red circles) are equal to emissions embodied in exports minus emissions embodied in imports. Green circles show what Scope 3 emissions would be if there was no difference in the emissions intensity of imported and exported goods—i.e. if the economic scale and economic structure were the only factors affecting Scope 3 emissions.

As typically developed cities outsourcing production through supply chains, Hong Kong and Macao are net importers of emissions. Such large imbalances in the volume of traded products can correspond to similarly large imbalances in the emissions embodied in traded products. For Hong Kong and Macao, the enormous unfavorable balance of trade (The volume for local products consumed in other regions is greater than the volume for local products consumed in other regions) is the most important factor resulting in their large per capita Scope 3 emissions, accounting for approximately 67% and 100% of Scope 3 emissions of Hong and Macao, respectively. A second factor influencing Scope 3 emissions is the emission intensity. The combination of a carbon-intensive power industry, relying primarily on coal, and of a relatively low value-added of industry thus translate into a high emission intensity of products. The high emission intensity (higher energy, lower added value) of the imports compared to local products in Hong Kong and Macao has gradually intensified the carbon transfer effect, resulting in approximately 36% and 13% of per capita Scope 3 emissions in Hong Kong and Macao respectively in 2015. In comparison, only approximately 1% of per capita Scope 3 emissions were related to differences in the sector responsible for import and export. Both Hong Kong and Macao are net importers of emissions. It is further shown in Fig. 7 that if the unfavorable balance of trade is eliminated, Macao and Hong Kong would still be net importers of emissions due to the increasingly significant impact of the emission intensity effect on Scope 3 emissions in recent years.

## 4. Discussion

As key developed gateway cities with frequent cross-boundary activities, Hong Kong and Macao play an irreplaceable role in promoting low-carbon and sustainable development in the world. Various gateway cities in the world need the information to develop sustainable economic development strategies. This study analyzes the carbon footprints of Hong Kong and Macao to provide reliable, self-consistent, transparent, and comparable data. The data could support for low-carbon policies, monitor the progress of mitigation measures, as well as further emissions-related research of cities, especially gateway cities.

Results indicate that the trend of Scope 1 carbon emissions from fuel combustion in Hong Kong and Macao have been stable or even declining during 2000–2015. As shown in Fig. 8, we compared our results with the estimates from local governments and other international institutes, including the British Petroleum(British Petroleum Company, 2019), Emissions Database for Global Atmospheric Research

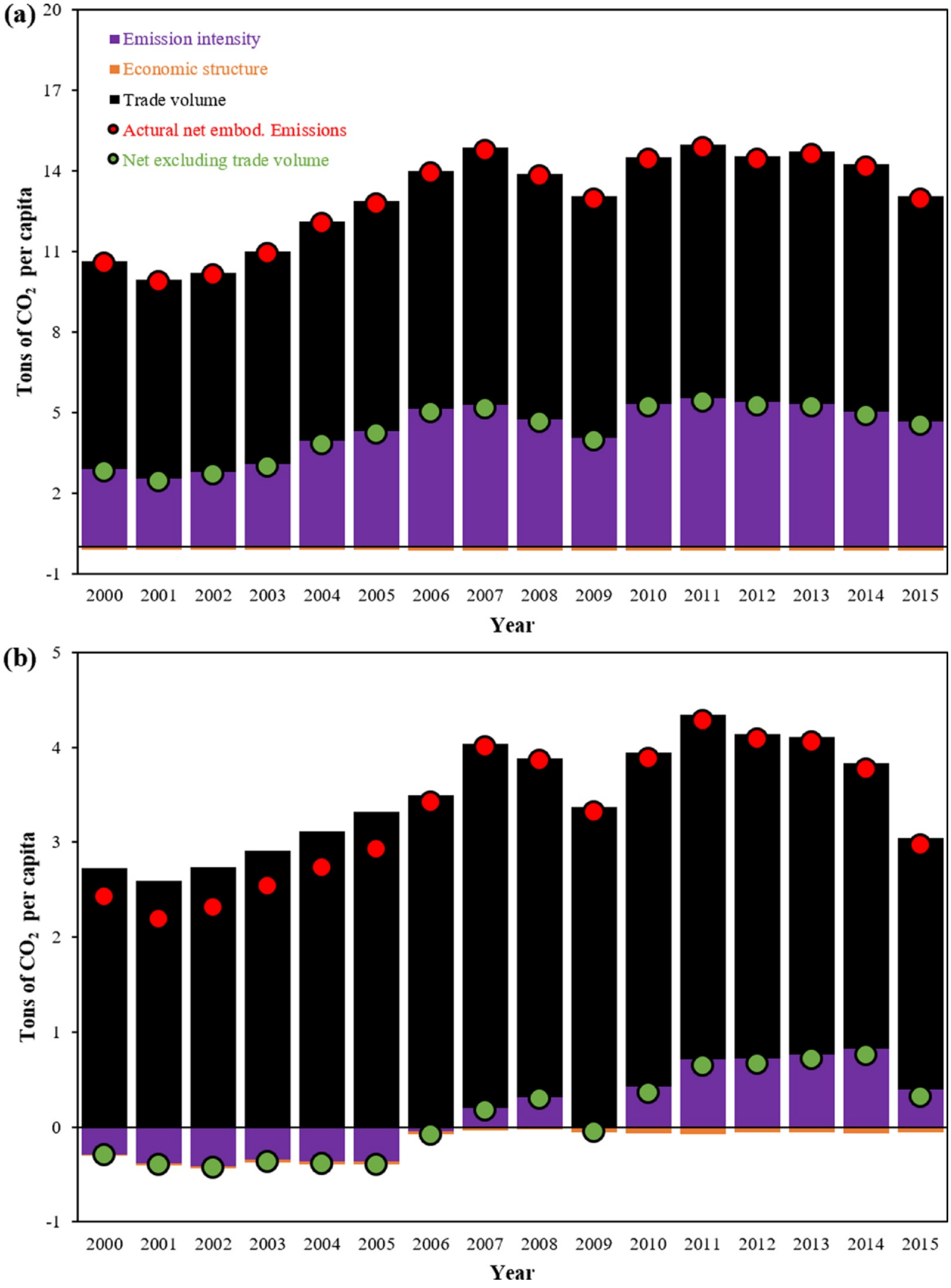

**Fig. 7.** Driving factors contributing to per capita Scope 3 emissions in Hong Kong and Macao (2000–2015).

(Crippa et al., 2019), Carbon Dioxide Information Analysis center (Gilfillan et al., 2019), and International Energy Agency (International Energy Agency, 2019)). Our estimated emissions were 4 to 53% lower than the highest value published by BP and had close results to those from most of the other institutes. Regarding Macao, our calculated emissions were similar to the estimation of EDGAR and CDIAC. While there were no abnormally high values in our estimates like CDIAC in 2009 or EDGAR in 2012 probably due to the uniformity and high quality of our data sources.

Our results also show that the indirect emissions (Scope 2 plus Scope 3) in these two cities were approximately twice as much as their direct emissions (Scope 1) and kept at a high level. Thus, their low-carbon urban planning should pay more attention to the embodied emissions outside the territory boundary. Hong Kong and Macao are special administrative regions with a high degree of autonomy and can take more effective actions on climate mitigation policies (Bulkeley, 2010). We thus propose specific recommendations for making low-carbon policy in Hong Kong and Macao based on our results as follows:

**Strengthen exchanges and cooperation with resource and energy suppliers to achieve low-carbon coordinated development with complementary advantages and technologies sharing.** The carbon footprints from the trade of Hong and Macao have also been mainly transferred to Mainland China with a lower level of technology. Meanwhile, it is confirmed that the impacts of higher emission intensity of imports on the growth of Scope 3 CO$_2$ emissions have become

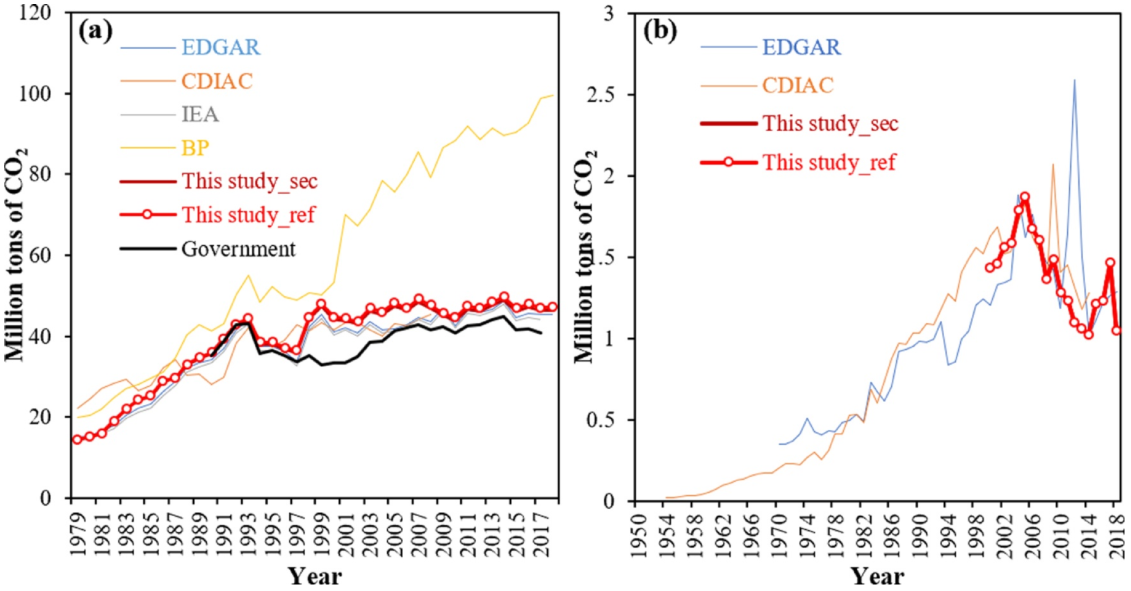

**Fig. 8.** Comparisons of the Reference Approach emissions (This study_ref), the Sectoral Approach emissions (This study*_sec*) in this study, and other existing emission inventories in Hong Kong(a) and Macao(b). Data source: Emissions Database for Global Atmospheric Research (EDGAR); Carbon Dioxide Information Analysis center (CDIAC); International Energy Agency (IEA); British Petroleum (BP); local government.

increasingly significant in this study. Based on the great potential for emission reduction in Mainland China confirmed by many studies (Davis and Caldeira, 2010; Kander et al., 2015; Mi et al., 2017), Hong Kong and Macao could share technologies with cooperative companies in Mainland China to improve carbon production efficiency. This is not only due to the low efficiency of CO$_2$ emissions in Mainland China but also due to Mainland China's role as the leading resource and energy supplier for Hong Kong and Macao. In addition, Macao has avoided local emissions from power generation by importing large amounts of electricity from Mainland China, mainly from carbon-intensive thermal power plants. Our research confirmed that since 2015, the imported power has become less carbon-intensive than the local power in Macao, which indicates the great potential for emission reduction in Mainland China. Thus, Macao could invest more capital in Mainland China's power industry, mainly focusing on environmental protection technology when investing, to improve carbon production efficiency.

**Take efficient measures to control emissions from urban infrastructure and use the urban metabolism framework to further track the future emissions from infrastructure.** *Manufacturing Industries and Construction (MIC)* sector is not carbon-intensive when only focusing on direct emissions. While it is an important contributor to the carbon footprints of Hong Kong and Macao when considering indirect emissions accumulated in the supply chain. Due to the needs of infrastructure and building construction in the context of accelerated urbanization, the enormous consumption demands of *MIC* will continue to keep in the following years. Therefore, efficient measures should be taken to promote low-carbon design, use low-carbon materials, and encourage low-carbon operation for infrastructure. Furthermore, some research shows that the carbon trapped in current urban infrastructure has also shown to be important as potential sources of future emissions (Chen et al., 2020). There is considerable evidence that the world is emitting a large amount of carbon, which is caused by the disposal of solid waste in landfills or incineration. It is worthwhile for cities to further track the potential fate of urban infrastructure under the urban metabolism framework to stabilize future global climate.

**Encourage low-carbon consumption patterns and develop local renewable energy.** Scope 3 emissions of Hong Kong and Macao increased rapidly, mainly due to the increasingly significant unfavorable balance of trade. For Hong Kong and Macao, trade is a strong driver in sustaining economic growth. Limiting growing consumer demand may be challenging as it usually grows with rapid economic growth. The government should encourage residents to enjoy low-carbon consumption patterns. Related measures include consumption of low-carbon products, electricity-saving and gas-saving in daily life, use of public transport rather than private cars, and purchase of electric bicycles and new energy vehicles(Chen et al., 2014). With the flexibility of autonomy, they would be able to implement tax reduction for low-carbon-intensive imported products. Appropriate Tax reduction policy will encourage consumers to choose low-carbon products and further promote the decarbonization of products sold to Hong Kong and Macao by upstream suppliers such as Mainland China. In addition, renewable energy has a huge potential for exploitation and application. For example, Macao's annual solar radiation is 5000 MJ/m$^2$, which is of great use-value(Chen et al., 2017). Therefore, they could vigorously promote the use of local renewable energy such as solar energy to reduce the dependence on traditional fossil fuels.

There are some limitations to this study. First, other drivers influencing CO$_2$ emissions embodied in trade per capita, such as education level, household size, and per capita residential area, need to be considered in further work. Second, although nuclear power does not produce carbon emissions in the power generation process, the system consumes materials and other fuels in facility construction, production, and operation activities, and thus indirectly generates carbon emissions from the perspective of the entire nuclear power chain system. This part of emissions should also be considered in future studies. In addition, the implementation of carbon capture, utilization, and storage technologies as the mitigation plan should also be discussed. Considering the long-term sustainable development of the city, the cost analysis of various mitigation plans should also be considered in the future.

## CRediT authorship contribution statement

**Xinyu Dou:** Writing - original draft, Methodology, Software, Writing - review & editing. **Zhu Deng:** Methodology, Writing - review & editing. **Taochun Sun:** Visualization. **Piyu Ke:** Visualization. **Biqing Zhu:** Writing - review & editing. **Yuli Shan:** Writing - review & editing. **Zhu Liu:** Conceptualization, Supervision, Funding acquisition.

## 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.

## Acknowledgments

Authors acknowledge the National Natural Science Foundation of China (grant 71874097 and 41921005), Beijing Natural Science Foundation(JQ19032), and the Qiu Shi Science & Technologies Foundation.

We thank Dr. Bofeng Cai and Drs. Pan He for their comments that helped improve this manuscript.

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