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# $CO_2$ emissions embodied in trade: Evidence for Hong Kong SAR

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A B S T R A C T

Cities play an important role in carbon emissions reduction and climate change mitigation. In this study, we examine the $CO_2$ emissions embodied in the imports and exports of the Hong Kong special administrative region (SAR) from 1990 to 2015 using the emissions embodied in bilateral trade (EEBT) method. The results show that Hong Kong SAR has been a net $CO_2$ importer and Mainland China plays a dominating role in the embodied $CO_2$ emissions of Hong Kong SAR. The sectors with high imported $CO_2$ emissions are mainly the energy sectors, such as electricity, heat, gas and water production and supply. Population density, GDP per capita, and trade openness have significantly positive effects on net $CO_2$ emissions increases in Hong Kong SAR, with population density taking the leading role. Population density increases by 1%, total net $CO_2$ emissions increase by 4%. Population slowdown scenario simulation results show that net $CO_2$ emissions of Hong Kong SAR could be reduced by 5.5%. Whereas, net $CO_2$ emissions of Hong Kong SAR could increase by 8.7% in the accelerated economic development scenario. Therefore, to reduce $CO_2$ emissions, Hong Kong SAR need control its population, develop the circular economy, and promote green lifestyle and consumption patterns.



## 1. Introduction

Global warming caused by fossil fuel combustion is one of the greatest challenges facing mankind (IPCC, 2014), and the 2018 IPCC report states that it may be necessary to limit the increase in atmospheric temperature rise to 1.5 °C rather than 2° above preindustrial levels (Mi et al., 2017). At present, more than 50% of the world's population lives in towns and cities (Fang et al., 2015), and the share of urban residents will rise to 68% by 2050[1] (UN, 2018). As the center of human activity, cities shoulder a critical responsibility in tackling climate change issues (Chen et al., 2018). Urban areas have been found to contribute more than 70% of $CO_2$ emissions (Lombardi et al., 2016), and $CO_2$ emissions increase by approximately 0.9% when the urbanization rate increases by 1% (Cai et al., 2018). Therefore, it is essential to study $CO_2$ emissions at the city level, to help decision makers and city planners develop effective policies (Shan et al., 2018).

Abundant research results have contributed greatly to the understanding of city carbon emissions. Many factors influence city energy consumption and $CO_2$ emissions, including city size (Li et al., 2018), development level (Shen et al., 2018), energy structure (Jiang et al., 2018), industrial structure (Liu and Bae, 2018), R&D investment (Cai et al., 2018), urban population scale (Miao, 2017), consumption characteristics, land use changes (Zhang et al., 2018), transportation (Wang et al., 2017), household income (Guo et al., 2018), floor area (Zhang et al., 2016), population density (Liu et al., 2017), and urban employment rate (Lin et al., 2017). The interactions among these factors increase the intricacy of the impacts of urbanization on city carbon emissions (Jiang et al., 2018).

Recent studies on China's city carbon emissions mainly address three aspects. One type of study defines the accounting boundaries for city carbon emissions and calculates the carbon emissions by selecting the case city. Most studies focus on the four municipalities (Beijing, Shanghai, Tianjin, Chongqing) (Feng et al., 2014; Huang et al., 2018a,b; Zhong et al., 2017) or on provincial capitals, such as Guangzhou (Wang et al., 2017) or Jinan (Qi et al., 2018), due to data accessibility and reliability (Chen et al., 2017). Because cities are playing an increasingly weighty role in China's total emissions reduction, more research has studied carbon emissions in other important cities (Liang et al., 2010; Mi et al., 2016; Shan et al., 2017).

Some studies examine the forces driving city carbon emissions

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[1] https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html.

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by adopting index decomposition analysis (IDA) (Xu and Ang, 2014), structural decomposition analysis (SDA) (Yuan and Zhao, 2016), the extended stochastic impacts by regression on population, affluence and technology (STIRPAT) model (Liu et al., 2017) and other spatial econometric models. For instance, the results of Jia et al. (2018) showed that economic output and population are the main causes of Nanchang's $CO_2$ emissions growth by adopting the logarithmic mean Divisia index (LMDI). Miao (2017) used an extended STIRPAT model to examine the key factors in energy consumption and $CO_2$ emissions for city residents. The results show that population size, affluence, and population compactness can increase energy consumption and $CO_2$ emissions. In contrast, Su et al. (2018) found that population agglomeration and some other factors, such as technological progress, improved trade openness, and the accessibility and density of roads, can lead to a reduction in carbon emissions.

In addition, some studies generate policy scenarios to simulate future emissions under different urbanization paths and assess the reduction potential for decision makers (Wang and Liang, 2013; Wu et al., 2016). For example, Shan et al. (2018) estimated $CO_2$ emissions for 182 Chinese cities, and the technological progress scenarios showed that substantial emissions reductions can be achieved. Zhu et al. (2017) proposed energy structure optimization, industrial restructuring, and energy efficiency as effective means for $CO_2$ emission reduction.

These studies have undoubtedly helped increase understanding of city carbon emissions and have provided valuable policy support to help China maintain a sustainable economic growth path and achieve low-carbon urban development. However, there is a lack of studies specifically focused on carbon emissions in international hub cities. Frequent international trade, limited energy, land and resources, and high population density may have a notable influence on the industrial structure and household consumption patterns and urban environment of these cities. With the promotion and implementation of the Belt and Road Initiative (BRI), there are more gateway cities in the world that need information to develop sustainable economic development strategies. These gateway cities will see more frequent import and export activities, which could impact their energy consumption. For example, trade openness increases coal consumption (Kurniawan and Managi, 2018) and leads to $CO_2$ emissions increases (Shahbaz et al., 2016). Thus, it may threaten the local environment and jeopardize the benefits brought by the BRI (Ascensão et al., 2018).

Therefore, to fill this gap, this study takes Hong Kong special administrative region (SAR) as a case to examine $CO_2$ emissions in this city and explore the relationship between $CO_2$ emissions and the urbanization process. We contribute to the literature in the following ways. First, we examine the $CO_2$ emissions embodied in the imports and exports of Hong Kong SAR with Mainland China and its top twenty trade partners using time series data from 1990 to 2015. Second, we quantitatively analyzed the impacts of population density, affluence, and openness on Hong Kong SAR's net $CO_2$ emissions. Third, We simulated future net $CO_2$ emissions per capita for Hong Kong SAR up to 2030 in different socioeconomic development scenarios.

## 2. Method and data

### 2.1. Emissions embodied in bilateral trade (EEBT) approach

Emissions embodied in bilateral trade (EEBT) and multiregional input-output (MRIO) methods are the mainstream approaches to calculating $CO_2$ emissions and other pollutants embodied in interregional trade (Feng et al., 2013; Huang et al., 2019). The EEBT approach is both more intuitive and more transparent (Peters, 2008); thus, the EEBT model is adopted in this study. Our starting point is the standard multiregional input-output relationship, and imports are removed to focus on domestic production.

$$\mathbf{x}^r = \mathbf{A}^{rr}\mathbf{x}^r + \mathbf{y}^{rr} + \sum_{s \neq r} \mathbf{e}^{rs} \tag{1}$$

where $r$ and $s$ denote different regions, $\mathbf{x}$ is total output, $\mathbf{A}$ is a matrix of intermediate consumption coefficients, $\mathbf{A}^{rr}$ represents region $r$'s industry requirements for domestically produced products, $\mathbf{y}$ is final consumption including household demand and fixed capital investment, $\mathbf{y}^{rr}$ is the domestic final consumption requirements of region $r$ provided by the industries in region $r$, $\mathbf{e}^{rs}$ is the exports from region $r$ to region $s$.

The $CO_2$ emissions caused by the domestic demand of region $r$ and the EEBT from region $r$ to region $s$ can be obtained from Equations (2) and (3):

$$\mathbf{F}^{rr} = \mathbf{f}^r(\mathbf{I} - \mathbf{A}^{rr})^{-1}\mathbf{y}^{rr} \tag{2}$$

$$\mathbf{F}^{rs} = \mathbf{f}^r(\mathbf{I} - \mathbf{A}^{rr})^{-1}\mathbf{e}^{rs} \tag{3}$$

where $\mathbf{F}^{rr}$ denotes the $CO_2$ emissions caused by the demand in region $r$, $\mathbf{F}^{rs}$ denotes the total direct and indirect $CO_2$ emissions in region r to produce the products that are exported to region s. $\mathbf{f}^r$ denotes the sectoral $CO_2$ emissions intensity of region $r$, which can be obtained by sectoral $CO_2$ emissions divided by the corresponding output.

Total $CO_2$ emissions embodied in the exports of region $r$ are

$$F^{re} = \sum_{s \neq r} \sum_i F_i^{rs} \tag{4}$$

where $F_i^{rs}$ is an element of matrix $\mathbf{F}^{rs}$ representing $CO_2$ emissions embodied in the exports of sector $i$ from region r to region s.

The production-based $CO_2$ emissions of region $r$ can be obtained by summing the $CO_2$ emissions caused by the domestic demand of region $r$ and the total $CO_2$ emissions embodied in the exports of region $r$. The consumption-based $CO_2$ emissions of region $r$ can be obtained by summing the $CO_2$ emissions caused by the domestic demand of region $r$ and the total $CO_2$ emissions embodied in the imports of region $r$. Some studies argue that consumption-based accounting approaches should include both direct and indirect emissions from final consumption activities associated with the settlement (Jones and Kammen, 2011; Larsen and Hertwich, 2010). It should be noted that consumption-based $CO_2$ emissions refer to the indirect $CO_2$ emissions embodied in the final consumption in this study, not considering direct $CO_2$ emissions caused by the end use of energy, such as heating and lighting. However, the comparison analysis of direct and indirect $CO_2$ emissions in Hong Kong SAR are given in the results and discussion section.

$$F_r^p = \sum_i F_i^{rr} + F^{re} \tag{5}$$

$$F_r^c = \sum_i F_i^{rr} + F^{rm} \tag{6}$$

where $F_i^{rr}$ is an element of matrix $\mathbf{F}^{rr}$ representing the $CO_2$ emissions of sector $i$ caused by the final consumption of region $r$. $F^{rm}$ represents the $CO_2$ emissions embodied in the imports of region $r$.

The net EEBT of region $r$ with region $s$ can be calculated according to

$$NEC^{rs} = \sum_i F_i^{rs} - \sum_i F_i^{sr} \quad (7)$$

If $NEC^{rs}$ are greater than zero, it means that region $r$ is a net $CO_2$ emissions exporter in its trade with region $s$. If $NEC^{rs}$ are smaller than zero, it means that region $r$ is a net $CO_2$ emissions importer in its bilateral trade with region $s$.

### 2.2. STIRPAT model

Dietz and Rosa (1997) proposed the STIRPAT (stochastic impacts by regression on population, affluence, and technology) model based on the classic IPAT model (Ehrlich and Holdren, 1971), the general formula for which is as follows:

$$I = aP^{b}A^{c}T^{d}\mu \quad (8)$$

In Equation (8), I stands for the environmental impact. P, A and T denote population, affluence and technology, respectively. coefficient a is the constant, while b, c and d are the exponential terms for P, A and T. $\mu$ is the error term. After taking the logarithm of both sides, Equation (8) can be rewritten as follows:

$$\ln I = a + b\ln P + c\ln A + d\ln T + \mu \quad (9)$$

In this paper, we used the net $CO_2$ emissions and net $CO_2$ emissions per capita as environmental indicators. Population density, GDP per capita, and openness are selected as the independent variables.

To investigate the existence of the environment Kuznets curve (EKC) in Hong Kong SAR, we add the quadratic term of GDP per capita in the model as shown in Equation (10).

$$\ln I = a + b\ln P + c\ln A + d\ln T + e\ln AA + \mu \quad (10)$$

Where, AA represents the quadratic term of per capita GDP. Ridge regression analysis is a nonlinear partial estimation method that is an improved form of OLS (ordinary least squares) regression. Although sacrificing some information and accuracy, ridge regression abandons the unbiasedness of OLS and yields a more realistic, more reliable regression equation. Thus, in this study, we chose ridge regression and use SPSS software.

### 2.3. Data

#### 2.3.1. Input-output data

The input-output table and $CO_2$ emissions data used in our study are taken from the Eora multiregion input-output (MRIO) database, which provides a time series of high-resolution IO tables with matching environmental and social satellite accounts for many countries (Lenzen et al., 2012). One country's economic output includes its domestic industries, final demand, and exports. MRIO tables from 1990 to 2015 for Hong Kong SAR and its top trading partners (1990–2015) are used in this study, including Mainland China, the USA, Japan, Germany, South Korea, the UK, Canada, India, Thailand, France, the Netherlands, Singapore, Italy, Malaysia, Indonesia, Australia, Spain, Mexico, Brazil, Russia, and Belgium. The economic data from the Eora database are valued in basic price. The satellite indicators include each sector's energy usage, $CO_2$ emissions and other air pollution, such as $SO_2$ emissions, PM10, and $NO_X$ emissions. Direct $CO_2$ emissions intensity is calculated for all sectors by dividing their emissions by their total output.

#### 2.3.2. Data sources

Population data, economic data and the area of Hong Kong SAR are shown in Table 1. The consumption data of each energy type can be obtained from Hong Kong Energy Statistics, and energy consumption structure of Hong Kong SAR is shown in Fig. 1. Openness represents the ratio of import and export to the GDP (Kurniawan and Managi, 2018; Shahbaz et al., 2016). The area data of Hong Kong SAR are obtained from the China Statistical Yearbook. Population and economic data are from the Census and Statistics Department of the government of the Hong Kong SAR. In this study, we examine the influencing factors from 2000 to 2015 due to a lack of openness and area data for the study period 1990–1999. Hong Kong SAR's population continued to increase during the study period, with an average annual increase rate of 0.6%. However, the average increase rate in Hong Kong SAR's area is only 0.05% due to limited land resources, which leads to high population density. In 2015, the population density increased to 6592 persons per square kilometer. The GDP per capita of Hong Kong SAR presents a rapidly increasing trend with an average increase rate of 3.4% during 2000–2015.

## 3. Results and discussion

### 3.1. Production-based and consumption-based $CO_2$ emissions of Hong Kong SAR

Hong Kong SAR's total and per capita production-based and consumption-based $CO_2$ emissions are shown in Fig. 2. Hong Kong SAR's production-based $CO_2$ emissions remained stable during the study period, increasing from 29 Mt in 1990 to 45 Mt in 1999 and then declining gradually to 36 Mt in 2015. In contrast, consumption-based $CO_2$ emissions showed some fluctuations. There was a small peak in 1995, and then they remained steady over the next few years. However, consumption-based $CO_2$ emissions increased sharply starting in 2002 and peaked in 2007. After joining the World Trade Organization (WTO), China further improved its import and export system, reducing the tariff barrier and expanding its market openness (Liu et al., 2016), which further reduced the import cost of manufactures in Hong Kong SAR and brought about a rapid increase in imports. These results are supported by the findings of (Levitt et al., 2018), who find that China's accession to the WTO increased the growth rate of consumption-based and imported emissions of its trading partners.

Affected by the global financial crisis, Hong Kong SAR's consumption-based $CO_2$ emissions dropped dramatically in 2008–2009. Subsequently, the consumption-based $CO_2$ emissions reached a peak value of 374 Mt in 2011 and then presented a decreasing trend, which may be related to improvement in the technological level of import products.

In terms of quantity, Hong Kong SAR's consumption-based $CO_2$ emissions were much greater than its production-based $CO_2$ emissions. The former were approximately 4–10 times the amount of latter during 2000–2015. The situation is similar for per capita $CO_2$ emissions, as shown in Fig. 2. Production-based $CO_2$ emissions per capita was approximately 5–7 tons from 1990 to 2015. However, Hong Kong SAR's consumption-based $CO_2$ emissions per capita increased from 18.5 tons in 1990 to 45.8 tons in 2015, with an annual growth rate of 4%. This increase occurred because Hong Kong SAR imported large amounts of emission-intensive agricultural and manufactured goods from Mainland China and other economies due to its extremely limited resource endowment, service-led industry structure, and enormous demand from residents (Davis and Caldeira, 2010; Harris et al., 2012). For instance, Hong Kong SAR imported paddies from Thailand and vegetables, fruit, wheat, rice, and beef cattle from Australia. Similar phenomena are found in London and Madrid (Andrade et al., 2018), Melbourne, Sydney, Brisbane, Adelaide, and Perth in Australia (Chen et al., 2016a,b), Tromsø in Norway (Larsen and Hertwich, 2010), and

**Table 1**
Socioeconomic data of Hong Kong SAR.

| | Population ($10^3$ persons) | GDP per capita (HKD) | Openness (%) | Area (square kilometers) | Population density (persons per square kilometers) |
|---|---|---|---|---|---|
| 2000 | 6665 | 200675 | 18.3 | 1098 | 6070 |
| 2001 | 6714 | 196765 | 18.8 | 1099 | 6109 |
| 2002 | 6744 | 192367 | 19.6 | 1101 | 6125 |
| 2003 | 6731 | 186704 | 20.6 | 1102 | 6108 |
| 2004 | 6784 | 194140 | 21.4 | 1103 | 6150 |
| 2005 | 6813 | 207263 | 22.5 | 1104 | 6171 |
| 2006 | 6857 | 219240 | 21.3 | 1104 | 6211 |
| 2007 | 6916 | 238676 | 20.2 | 1104 | 6265 |
| 2008 | 6958 | 245406 | 20.8 | 1104 | 6302 |
| 2009 | 6973 | 237960 | 19.6 | 1104 | 6316 |
| 2010 | 7024 | 252887 | 19.7 | 1104 | 6363 |
| 2011 | 7072 | 273549 | 21.1 | 1104 | 6405 |
| 2012 | 7150 | 284899 | 20.4 | 1104 | 6477 |
| 2013 | 7179 | 297860 | 19.7 | 1104 | 6503 |
| 2014 | 7230 | 312609 | 19.1 | 1105 | 6543 |
| 2015 | 7291 | 328924 | 18.1 | 1106 | 6592 |

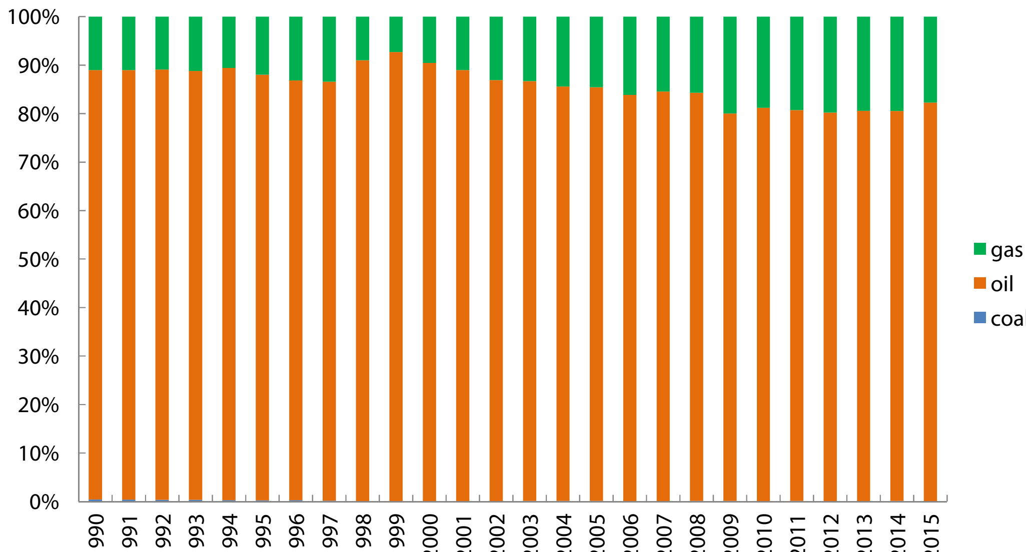


**Fig. 1.** Energy consumption structure of Hong Kong SAR.

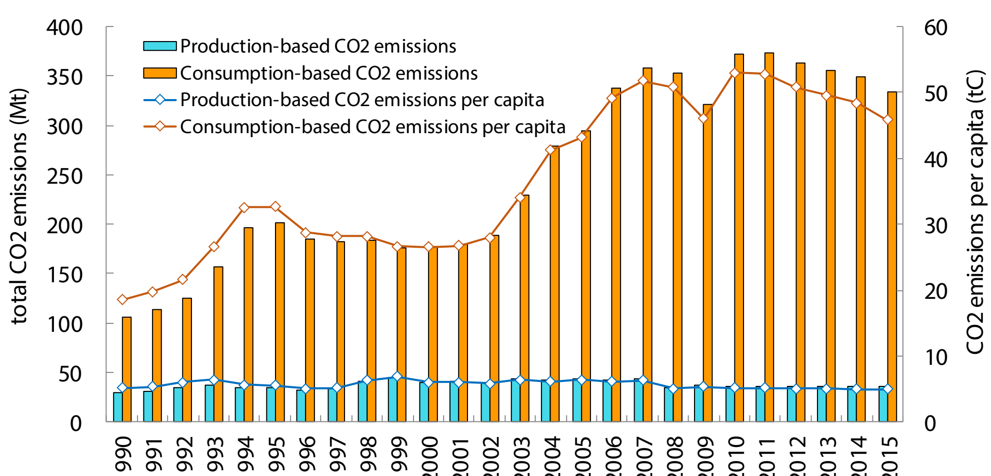


**Fig. 2.** Hong Kong SAR's total and per capita production-based and consumption-based $CO_2$ emissions.

many developed cities in Mainland China (Feng et al., 2013, 2014; Meng et al., 2017; Mi et al., 2016) where per capita GHG emissions are much larger under consumption-based methodologies.

Per capita consumption-based $CO_2$ emissions of Hong Kong SAR are compared with the results in other studies as shown in Table 2. Due to different data sources and study periods, the results varied at different extents. In addition, the boundary of consumption-based accounting at urban level are defined differently, which could lead to different results (Chavez and Ramaswami, 2013; Chen et al., 2019; Lin et al., 2015). For example, according to the definition of Lin et al. (2015), consumption-based $CO_2$ emissions include both direct and indirect $CO_2$ emissions at local level. To get a whole grasp of consumption-based $CO_2$ emissions in Hong Kong SAR, we calculated the direct $CO_2$ emissions of Hong Kong SAR, and the results are given in Fig. 3. We can see that the direct $CO_2$ emissions of Hong Kong SAR are dominated by oil and gas. Both the total and per capita direct $CO_2$ emissions increased significantly after the return of Hong Kong to China, and reached to peak in 1999. Afterwards, they showed a downward trend. By comparing the direct and indirect $CO_2$ emissions in Fig. 4, we find that direct $CO_2$ emissions in Hong Kong SAR only account for a very small percentage in its total consumption-based $CO_2$ emissions.

Compared to other cities in Mainland China, both the total consumption-based $CO_2$ emissions and per capita consumption-based $CO_2$ emissions in Hong Kong SAR are much larger, even for the most developed and populous cities, such as Beijing, Shanghai, and Tianjin (Mi et al., 2016). For example, in 2007, per capita consumption-based $CO_2$ emissions in Hong Kong SAR were approximately 4–5 times the levels in Beijing, Tianjin, and Shanghai (Feng et al., 2013; Huang et al., 2018a,b). This reflects the urgent need to control population growth in Hong Kong SAR. Urbanization may reduce energy consumption per capita and promote energy efficiency due to aggregation and scale effects. However, it could also bring about an increase in energy consumption when large amounts of goods and services are imported to meet residents' demand (Liu et al., 2017). In February 2019, the central government of China and the State Council released a development plan for the Guangdong-Hong Kong-Macao Greater Bay Area that aims to promote coordinated regional economic development by building on the four core cities of Hong Kong, Macao, Guangzhou and Shenzhen as supplying core energy for regional development and leading the development of nearby regions, including Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing, through a radiation effect. This plan will be helpful for Hong Kong SAR's population dispersion and $CO_2$ emissions reduction.

### 3.2. Embodied $CO_2$ emissions in the imports and exports of Hong Kong SAR

As shown in Table 3, there is a large amount of $CO_2$ emissions embodied in Hong Kong SAR's imports and exports. $CO_2$ emissions embodied in the imports and exports of Hong Kong SAR increased during 1990–2015, with annual increases of 5.5% and 4.5%, respectively. Hong Kong SAR has been a net $CO_2$ importer. For example, the net $CO_2$ emissions of Hong Kong SAR were 298 Mt in 2015. $CO_2$ emissions embodied in the imports of Hong Kong SAR were approximately 94% of its consumption-based $CO_2$ emissions in 2015, which were much larger than those of many developed countries, such as Sweden and the UK, whose imported $CO_2$ emissions account for more than 30% of their consumption-based emissions (Davis and Caldeira, 2010).

The embodied $CO_2$ emissions in the imports and exports of Hong Kong SAR in 2015 are shown in Fig. 5 and Fig. 6. Hong Kong SAR imported most of its $CO_2$ emissions from Mainland China, followed by the USA, Japan, South Korea, and India. Meanwhile, Hong Kong SAR exported its $CO_2$ emissions to Mainland China, the USA, some southeast Asian countries and Europe countries, such as Singapore, Malaysia, and the UK.

Hong Kong SAR has outsourced large amounts of $CO_2$ emissions to Mainland China, with the share surpassing 80% since 2004. Meanwhile, there are large amounts of $CO_2$ emissions embodied in the exports of Hong Kong SAR to Mainland China, with the share exceeding one-third since 2003. These trends are related to a series of policy implementations. After China joined the WTO, its import and export trade increased significantly. Mainland China surpassed the USA to become Hong Kong SAR's largest trade partner in 2003, and Hong Kong SAR has been an important port city serving as a bridge between other countries and Mainland China. To promote common economic prosperity and development between Mainland China and Hong Kong SAR, the central government of China and the Hong Kong SAR signed the Closer Economic Partnership Arrangement (CEPA) in June 29, 2003, which mainly aimed to achieve zero tariffs on goods traded between them, to expand market access for

**Table 2**
Consumption-based $CO_2$ emissions per capita comparison (tC).

| Sources | Study area | $CO_2$ emissions per capita | Scope | Study period |
|---|---|---|---|---|
| Hillman and Ramaswami (2010) | The average of eight US cities (Denver, CO, Boulder, CO, Ft Collins, CO, Arvada, CO, Portland, OR, Seattle, WA, Minneapolis, MN, Austin, TX) | 21.9 | direct + indirect | – |
| Andrade et al. (2018) | London, UK | 81.1 | direct + indirect | 2010 |
| | Madrid, Spain | 28.2 | | |
| Larsen and Hertwich (2010) | Tromsø, Norway | 49 | direct + indirect | 2007 |
| Dias et al. (2014) | Aveiro, Portugal | 9.5 | direct + indirect | 2005 |
| Chen et al. (2016a) | Sydney, Australia | 16 | indirect | 2009 |
| | Perth, Australia | 31 | | |
| | HongKong SAR | 33 | | |
| Davis and Caldeira (2010) | Luxembourg | 34.7 | indirect | 2004 |
| | US | 22.0 | | |
| | Singapore | 20.2 | | |
| | HongKong SAR | 14.8 | | |
| Feng et al. (2014). | Beijing, China | 9.8 | indirect | 2007 |
| | Shanghai, China | 11.3 | | |
| | Tianjin, China | 10.0 | | |
| Hertwich and Peters (2009) | HongKong SAR | 29.0 | indirect | 2001 |
| This study | HongKong SAR | 26.7 | indirect | 2001 |
| | | 41.2–53.0 | | 2004–2015 |
| | | 43.1–54.4 | direct + indirect | |

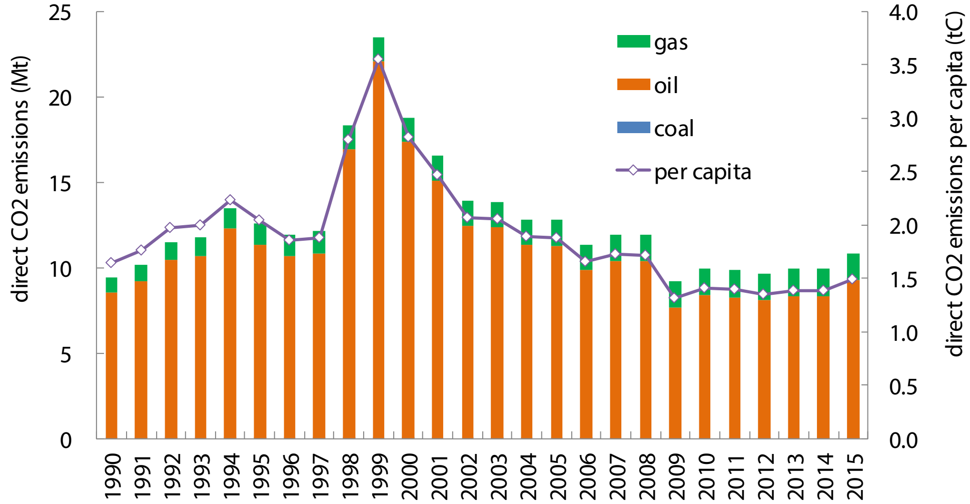


**Fig. 3.** The total and per capita direct $CO_2$ emissions of Hong Kong SAR.

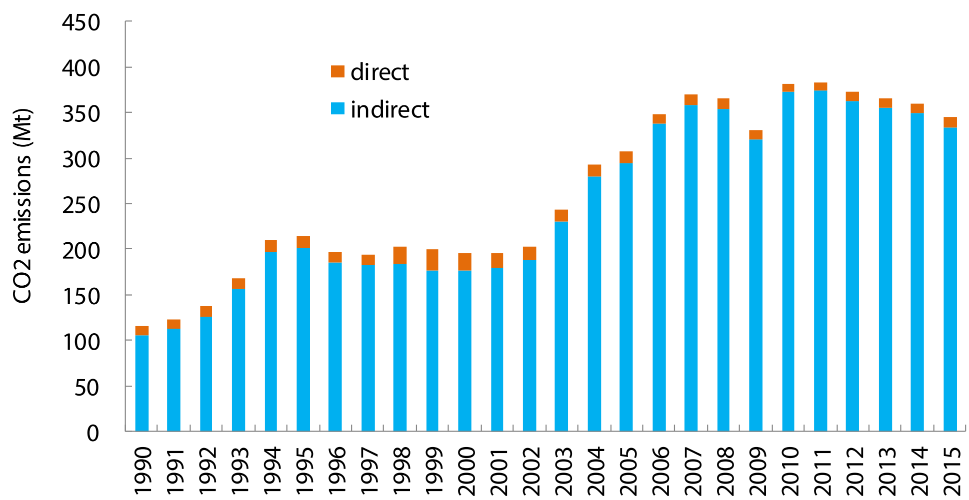


**Fig. 4.** The comparison of direct and indirect $CO_2$ emissions of Hong Kong SAR.

service trade, and to facilitate trade and investment. In addition, the government of Hong Kong SAR implemented an investment immigration policy at the end of 2003, which promotes the flow of capital and people from Mainland China into Hong Kong SAR. This policy also leads to a greater demand for products and services, resulting in more embodied $CO_2$ emissions. For example, the rate of increase for $CO_2$ emissions embodied in the trade from Mainland China to Hong Kong SAR exceeded 32% during 2003–2004. The $CO_2$ emissions embodied in trade from Hong Kong SAR to Mainland China have been greater than the total $CO_2$ emissions of Hong Kong SAR to other top economies since 2007.

### *3.3. High emission sectors in the imports of Hong Kong SAR*

Since most $CO_2$ emissions embodied in the imports of Hong Kong SAR are mainly from Mainland China, we further examine these $CO_2$ emissions at sectoral level. We aggregated 123 sectors into sixteen categories for the convenience of discussion, each category and its corresponding sectors are given in Table S1. As shown in Fig. 7, the category with high imported $CO_2$ emissions are mainly the energy sectors. 57.2% of $CO_2$ emissions embodied in the exports from Mainland China to Hong Kong SAR are from electricity, heat, gas and water production and supply in 2015. Similar situation can be found in USA, South Korea, Japan, and Australia. For instance, 16%, 14% and 11% of $CO_2$ emissions embodied in the exports from the USA to Hong Kong SAR are from electric power generation, transmission, and distribution; natural gas distribution; and petroleum refineries, respectively. Approximately 34% and 22% of the total exported $CO_2$ emissions from South Korea to Hong Kong SAR are concentrated in electric services and in gas and water supply, respectively. 23% of the total exported $CO_2$ emissions from Japan to Hong Kong SAR are in electric power for enterprise use. 34% of the total exported $CO_2$ emissions from Australia to Hong Kong SAR are in electricity supply.

In addition, Hong Kong SAR imported large amounts of $CO_2$ emissions from the emission-intensive manufacturing sectors of Mainland China, such as textiles, equipment manufacturing, and metal smelting & rolling processing industry. This is related to the

**Table 3**
Hong Kong SAR's $CO_2$ emissions embodied in imports and exports (Mt).

| | EEI | Mainland China | % | Other economies | % | EEE | Mainland China | % | Other economies | % |
|---|---|---|---|---|---|---|---|---|---|---|
| 1990 | 82 | 51 | 62 | 31 | 38 | 5 | 0 | 9 | 5 | 91 |
| 1991 | 88 | 55 | 63 | 33 | 37 | 5 | 1 | 11 | 5 | 89 |
| 1992 | 97 | 59 | 61 | 38 | 39 | 6 | 1 | 12 | 5 | 88 |
| 1993 | 126 | 85 | 68 | 41 | 32 | 7 | 1 | 17 | 6 | 83 |
| 1994 | 168 | 124 | 74 | 44 | 26 | 6 | 1 | 18 | 5 | 82 |
| 1995 | 173 | 125 | 72 | 48 | 28 | 6 | 1 | 21 | 5 | 79 |
| 1996 | 158 | 111 | 70 | 47 | 30 | 6 | 1 | 22 | 5 | 78 |
| 1997 | 155 | 108 | 70 | 47 | 30 | 6 | 1 | 22 | 5 | 78 |
| 1998 | 151 | 107 | 71 | 44 | 29 | 8 | 2 | 24 | 6 | 76 |
| 1999 | 140 | 99 | 71 | 41 | 29 | 9 | 2 | 25 | 7 | 75 |
| 2000 | 145 | 100 | 69 | 45 | 31 | 8 | 2 | 26 | 6 | 74 |
| 2001 | 148 | 103 | 70 | 44 | 30 | 9 | 3 | 29 | 6 | 71 |
| 2002 | 159 | 114 | 72 | 44 | 28 | 9 | 3 | 32 | 6 | 68 |
| 2003 | 198 | 153 | 77 | 46 | 23 | 12 | 5 | 39 | 7 | 61 |
| 2004 | 251 | 202 | 81 | 49 | 19 | 13 | 6 | 43 | 8 | 57 |
| 2005 | 265 | 214 | 81 | 51 | 19 | 14 | 6 | 45 | 8 | 55 |
| 2006 | 311 | 259 | 83 | 52 | 17 | 15 | 7 | 46 | 8 | 54 |
| 2007 | 331 | 278 | 84 | 53 | 16 | 16 | 8 | 50 | 8 | 50 |
| 2008 | 332 | 278 | 84 | 54 | 16 | 14 | 7 | 51 | 7 | 49 |
| 2009 | 297 | 247 | 83 | 51 | 17 | 14 | 7 | 53 | 6 | 47 |
| 2010 | 351 | 295 | 84 | 56 | 16 | 15 | 9 | 58 | 6 | 42 |
| 2011 | 353 | 296 | 84 | 57 | 16 | 16 | 10 | 61 | 6 | 39 |
| 2012 | 343 | 286 | 84 | 56 | 16 | 16 | 10 | 62 | 6 | 38 |
| 2013 | 335 | 277 | 83 | 58 | 17 | 15 | 10 | 62 | 6 | 38 |
| 2014 | 329 | 273 | 83 | 56 | 17 | 15 | 10 | 63 | 6 | 37 |
| 2015 | 313 | 257 | 82 | 57 | 18 | 15 | 10 | 63 | 6 | 37 |

Notes: EEI denotes $CO_2$ emissions embodied in imports. EEE denotes $CO_2$ emissions embodied in exports.


**Fig. 5.** $CO_2$ emissions embodied in the imports of Hong Kong SAR in 2015 (Mt).

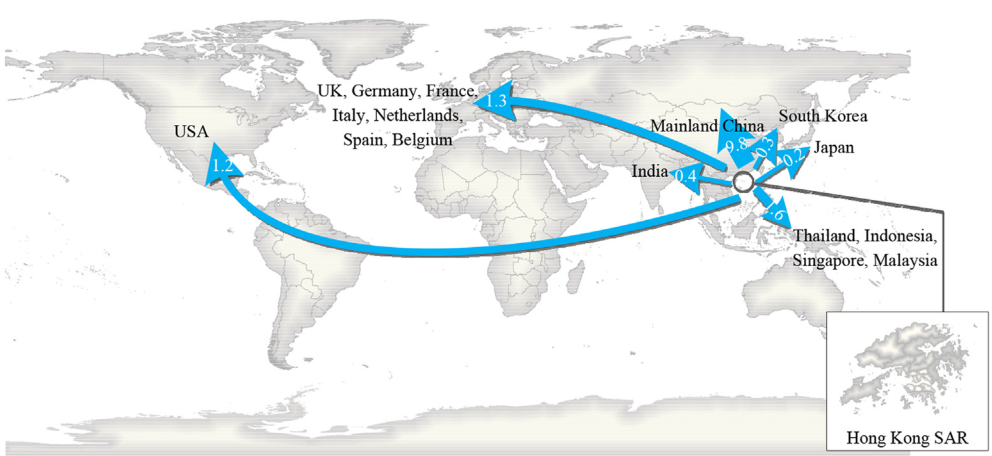


**Fig. 6.** $CO_2$ emissions embodied in the exports of Hong Kong SAR in 2015 (Mt).

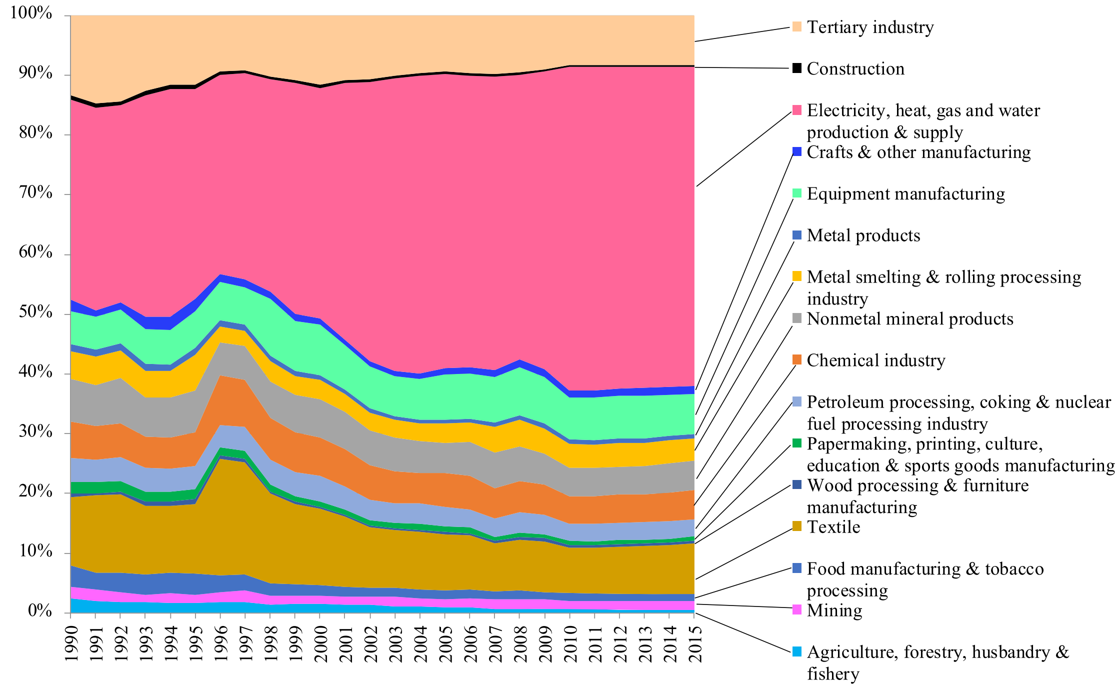


**Fig. 7.** $CO_2$ emissions embodied in the imports of Hong Kong SAR from Mainland China in 2015.

energy structure of Mainland China being dominated by coal and a low technological level. Moreover, there are substantial $CO_2$ emissions embodied in transportation. For instance, 25% of total exported $CO_2$ emissions from the USA to Hong Kong SAR are concentrated in the truck transportation sector, and 12% of total exported $CO_2$ emissions from Australia to Hong Kong SAR are in road freight. These results are supported by the findings of other authors (Eriksson et al., 2016; Fathollahi et al., 2018), whose results show that the production and distribution of wine and crops cause increased $CO_2$ emissions and environmental impacts due to the inputs of machinery and diesel fuel, fertilizers, and transportation.

### 3.4. Regression results analysis

In this paper, total net $CO_2$ emissions are defined as the dependent variable, and population density (P), GDP per capita (A), and trade openness (T) are taken as independent variables. From the estimation results in Table 4, population density, GDP per capita, and trade openness have significant positive effects on the total net $CO_2$ emissions of Hong Kong SAR. Among these factors, population density has the greatest positive impact on total net $CO_2$ emissions. When population density increases by 1%, total net $CO_2$ emissions increase by 4%, which indicates that population density is the main driving force of net $CO_2$ emissions growth in Hong Kong SAR. This is because a large amount of goods and services are imported (Harris et al., 2012). Thus, net $CO_2$ emissions increase with increasing population density. These results are supported by the findings of Miao (2017), whose results illustrate that population compactness promotes residential energy consumption, causing $CO_2$ emissions to increase significantly.

Trade openness also significantly increased the total net $CO_2$ emissions of Hong Kong SAR. with a 1% increase in trade openness, net $CO_2$ emissions increase by 2.7%. These results are consistent with the findings of Kurniawan and Managi (2018), whose results demonstrate that trade increases coal consumption in Indonesia. Similar results are found by Shahbaz et al. (2016), who conclude that trade openness increases $CO_2$ emissions in Malaysia.

**Table 4**
Estimation results for total net $CO_2$ emissions as the dependent variable.

| Variables | B | SE(B) | Beta | T | Sig |
|---|---|---|---|---|---|
| lnP | 4.0129 | 1.3063 | .3333 | 3.0719 | .0097 |
| lnA | .9103 | .1928 | .5130 | 4.7223 | .0005 |
| lnT | 2.7446 | .5889 | .4886 | 4.6841 | .0005 |
| Constant | −42.1538 | 10.8533 | .0000 | −3.8840 | .0022 |
| R-squared | .8499 | | | | |
| F value | 22.6588 | | | | |
| Sig F | .0000 | | | | |

GDP per capita also has a positive impact on total net $CO_2$ emissions: a 1% increase in GDP per capita increases total net $CO_2$ emissions by 0.9%. This is supported by the findings of Minx et al. (2013), Lin et al. (2017), and Miao (2017), whose results show that affluence leads to $CO_2$ emissions increases.

The results with net $CO_2$ emissions per capita as the dependent variable are similar to those for total net $CO_2$ emissions, as shown in Table 5. Population density, GDP per capita, and trade openness have positive impacts on net $CO_2$ emissions per capita, with population density taking the leading role, followed by trade openness. To test the EKC hypothesis, we add the square of affluence (GDP per capita) as an explanatory variable when per capita $CO_2$ emissions are the dependent variable in the STIRPAT model; the regression results are shown in Table 6. The coefficient of the square of affluence is significantly positive, which implies that $CO_2$ emissions continue to increase with economic growth in Hong Kong SAR.

### 3.5. Scenarios analysis

Based on the regression results, we simulate future net $CO_2$ emissions per capita of Hong Kong SAR under different scenarios. According to the historical data of population, GDP per capita, and openness, we calculated their average increase rates during

**Table 5**
Estimation results for net $CO_2$ emissions per capita as the dependent variable.

| Variables | B | SE(B) | Beta | T | Sig |
|---|---|---|---|---|---|
| lnP | 3.4788 | 1.3024 | .3113 | 2.6710 | .0204 |
| lnA | .8372 | .1922 | .5082 | 4.3563 | .0009 |
| lnT | 2.6735 | .5842 | .5127 | 4.5765 | .0006 |
| Constant | −45.2090 | 10.8207 | .0000 | −4.1780 | .0013 |
| R-squared | .8269 | | | | |
| F value | 19.1114 | | | | |
| Sig F | .0001 | | | | |

**Table 6**
Estimation results for the EKC test.

| Variables | B | SE(B) | Beta | T | Sig |
|---|---|---|---|---|---|
| lnP | 2.0594 | 1.5258 | .1843 | 1.3498 | .2042 |
| lnA | .5381 | .1262 | .3267 | 4.2653 | .0013 |
| lnT | 2.7300 | .5995 | .5235 | 4.5537 | .0008 |
| LnA_SQ | .2669 | .0632 | .3271 | 4.2201 | .0014 |
| Constant | −35.8688 | 11.8751 | .0000 | −3.0205 | .0116 |
| R-squared | .8339 | | | | |
| F value | 13.8103 | | | | |
| Sig F | .0003 | | | | |

2000–2015, respectively. The increase rate of population, GDP per capita, and openness are 0.55%, 3.42%, and 0.03%, respectively. Future net $CO_2$ emissions per capita up to 2030 are predicted based on the current increase rates of population, GDP per capita, and openness, which is marked as BAU scenario. We made six scenarios, including accelerated economic development, accelerated population development, accelerate opening up, economic slowdown, population slowdown, and slowdown in opening up. In each accelerated scenario, the corresponding growth rate increases by 20%. While, the corresponding growth rate decreases by 20% in each slowdown scenario. Scenarios setting of each are given in Table 7.

The net $CO_2$ emissions per capita up to 2030 in BAU and six scenarios are shown in Fig. 8. Net $CO_2$ emissions per capita of Hong Kong SAR will increase to approximately 88.3 tC following the current increase rates of population, GDP per capita, and openness. It will increase up to around 96 tC and 94 tC in the accelerated economic development scenario and accelerated population development scenario, respectively. On the contrary, net $CO_2$ emissions per capita of Hong Kong SAR will decrease to 81.3 tC and 83.4 tC in economic slowdown scenario and population slowdown scenario, respectively. By compare the results, we find that net $CO_2$ emissions per capita of Hong Kong SAR in accelerated opening up and slowdown in opening up scenarios are close to those in BAU scenario. This is due to the steady openness of Hong Kong SAR over years. Therefore, it is important to control the population of Hong Kong SAR, and keep economic sustainable development to reduce

**Table 7**
Scenarios settings (%).

| Scenarios | Increase rate of population | Economic increase rate | Increase rate of openness |
|---|---|---|---|
| BAU | 0.552 | 3.424 | 0.027 |
| Accelerated economic development | 0.552 | 4.109 | 0.027 |
| accelerated population development | 0.663 | 3.424 | 0.027 |
| accelerate opening up | 0.552 | 3.424 | 0.032 |
| economic slowdown | 0.552 | 2.739 | 0.027 |
| population slowdown | 0.442 | 3.424 | 0.027 |
| slowdown in opening up | 0.552 | 3.424 | 0.022 |

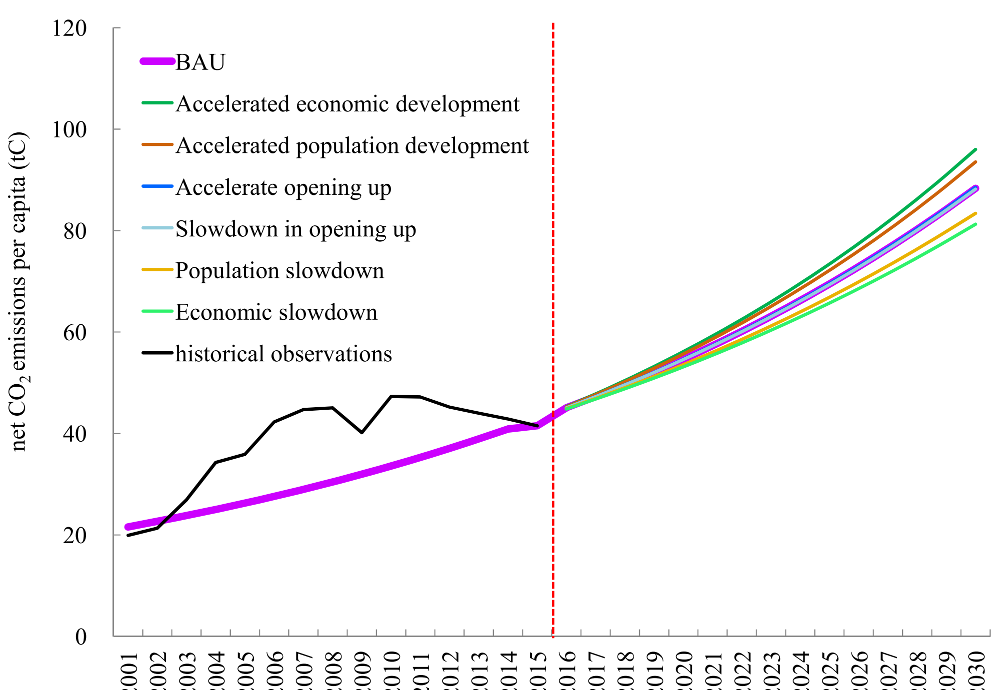


**Fig. 8.** Net $CO_2$ emissions per capita of Hong Kong SAR in different scenarios.

net $CO_2$ emissions per capita.

## 4. Conclusions

The study of carbon emissions at the city level plays an important role in emissions reduction policy formulation and implementation, which could significantly affects the process of climate change mitigation. In this study, we examined the $CO_2$ emissions embodied in Hong Kong SAR's imports and exports using the EEBT method. The results show that Hong Kong SAR has been a net $CO_2$ emission importer due to limited resource endowment and high consumption demand. Hong Kong SAR outsourced most of its $CO_2$ emissions to other economies. Mainland China has been playing a significant role in the $CO_2$ emissions embodied in imports and exports of Hong Kong SAR due to the increasingly frequent commercial intercourse.

Population density, GDP per capita, and trade openness significantly contribute to the increase of net $CO_2$ emissions in Hong Kong SAR, with population density taking the leading role. Population density increases by 1%, total net $CO_2$ emissions increase by 4%. Simulation results show that net $CO_2$ emissions of Hong Kong SAR could be reduced by 5.5% in population slowdown scenario. With the development of the Guangdong-Hong Kong-Macao Greater Bay Area, it is important for China to promote the coordinated economic development of the Pearl River Delta region and accelerate the urbanization process in key node cities, such as Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing. More job opportunities need to be provided in these cities to control the population of Hong Kong SAR, thereby reducing the related $CO_2$ emissions. In addition, scenario simulation results shows that net $CO_2$ emissions of Hong Kong SAR could increase by 8.7% in the accelerated economic development scenario. Thus, the government of Hong Kong SAR should advocate a green lifestyle and consumption patterns to reduce $CO_2$ emissions from the consumer side, such as encouraging the purchase of practical products instead of luxury goods, increasing the financial support for energy-saving buildings, and promoting the development of circular economy.

There are some limitations to this study. First, the consumption-based emissions of Hong Kong SAR may be greater because only Mainland China and its top twenty trade partners are considered. Second, other factors influencing consumption-based $CO_2$ emissions per capita, such as education level, household size and per capital residential area, need to be considered in further work.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.117918.

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