Renewable and Sustainable Energy Reviews 67 (2017) 662–672

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Decoupling analysis on energy consumption, embodied GHG emissions and economic growth — The case study of Macao

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ARTICLE INFO

Article history:
Received 12 July 2015
Received in revised form
6 March 2016
Accepted 9 September 2016
Available online 25 October 2016

Keywords:
Decoupling indicator
Embodied
Sustainable development
Macao

ABSTRACT

Decoupling analysis is considered to be an appropriate approach to evaluate the process of sustainable development. However, decoupling indicator based on terminal measurement neglects the external effect such as trade, which couldn't reflect an economy's decoupling degree systematically and comprehensively. Thus, this paper adopts embodied (direct plus indirect) greenhouse gas (GHG) emissions to acquire the decoupling indicators in Macao from 2000 to 2013. As for total embodied GHG emissions (TEGE), the results reveal that Macao's economy has experienced four decoupling stages, with a distinct tendency towards strong decoupling. When comparing decoupling indicators of TEGE in terms of systematic accounting with that of direct accounting, many differences can be seen. As for total energy consumption (TEC), Macao's TEC has decoupled from its economic growth. The energy related GHG emissions, however, strongly coupled with TEC. As a result, energy-saving and emission mitigation measures can be devised for Macao according to the decoupling results. This work is the first assessment of Macao's decoupling degrees.

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http://dx.doi.org/10.1016/j.rser.2016.09.027

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1. Introduction

In recent decades the global economy has witnessed the rapid growth, which is, however, achieved at the cost of energy resource depletion and environment degradation. Taking the year of 2012 as an example, global energy consumption and related greenhouse gas (GHG) emissions increased by about 25% and 30% compared to the level of 2002, with a quantity of 12483.2 Mtoe (Million tonnes of oil equivalent) and 31734 Mt CO_2, respectively [1,2]. Excessive energy consumption and GHG emissions have caused severe problems such as pollution and climate change, which pose threats to human society. As humankind is confronted with these challenges, it's of great significance to initiate sustainable development, whose oft-quoted definition is "development that meets the need of the present without compromising the ability of future generations to meet their own needs" [3]. In scientific research area, different indicators were proposed to evaluate sustainable development. Among all the indicators, the decoupling indicator is considered to be an appropriate indicator to evaluate the process of sustainable development.

The decoupling theory was first systematically studied by Wuppertal Institute. They came up with the 'Factor Four' revolution for the developed countries, namely, doubling wealth and halving resource use in the following 50 years to decouple the resource use from economic growth [4]. Zhang is the first researcher who adopted the decoupling theory to analyze the link between CO_2 emission and economic growth [5]. To our knowledge, OECD is the first international organization, which simply defined decoupling as breaking the link between 'environmental bads' and 'economic goods' [6]. OECD also identifies five interlinked objectives for enhancing cost-effective and practical environmental policies in the context of sustainable development, one of which is decoupling environmental pressure from economic growth [6,7]. Since then, the notion of decoupling has been globally recognized as a significant conceptualization of sustainable development. For example, Vehmas et al. used the decoupling theory to analyze the relationship between total energy supply and CO_2 emissions in EU, Japan, USA, China, India and Brazil [8]. In 2004, Peter and Henri provided an empirical analysis of decoupling economic growth and energy use across 10 manufacturing sectors in 14 OECD countries [9].

Generally, total energy consumption (TEC) and GHG emissions are always coupled with the economic growth. In most situations, they are rising simultaneously. On account of this, many efforts have been made to decouple TEC and GHG emissions from economic growth. In order to measure the decoupling degree, many scientific and feasible decoupling indicators were established. OECD measured decoupling indicators by having an environmental pressure variable for numerator and an economic variable as denominator. According to the results, it divided decoupling into 2 stages [10]. But in the process of economic growth, there is not only decoupling phenomena, but also coupling phenomena. In term of this, Vehmas et al. structured a comprehensive framework of the different aspects of decoupling [8]. Based on that, 8 more specific decoupling degrees had been presented by Tapio in the case study of road traffic in Finland, in which the decoupling degree was expressed as elasticity values under 1.0 [11]. Though there are different kinds of measuring methods for decoupling, no standard method is applicable for every case. Nowadays, researchers have widely applied the decoupling analysis in a variety of studies. For instance, Lu et al. adopted the Divisia index approach to analyze the decoupling effects among economic growth, transport energy demand and CO_2 emission in Germany, Japan, South Korea and Taiwan during 1990–2002 and found that Energy conservation performance and CO_2 mitigation in each country are strongly correlated with environmental pressure and economic driving force, except for Germany in 1993 and Taiwan during 1992–1996 [12]. Charlita and Kaneko examined the occurrence of decoupling between the growth rates in economic activity and CO_2 emission from energy consumption in Brazil from 2004 to 2009 to point out that there existed an absolute decoupling in 2009 [13]. By utilizing the LMDI (log mean Divisia index) method, Zhang and Da decomposed the change of China's carbon emission and carbon emission intensity from 1996 to 2010 in order to find the efficient ways to reduce carbon emission intensity in China [14]. For provincial level, the decoupling index presented by Tapio was applied to identify the decoupling degrees between the growth rates in economic activity and CO_2 emission from energy consumption in Jiangsu from 1995 to 2009, and the results showed that the whole Jiangsu economy experienced weak decoupling and strong decoupling except 2003–2005 [15].

These existing studies have contributed greatly to the decoupling analysis, which also provide helpful references for decoupling analysis in this paper. But it's far from enough. Firstly, previous research focused on the decoupling indicators consider only direct GHG emissions occurring within the territorial boundary on the ground of IPCC framework, but neglect the indirect GHG emissions associated with goods and services imported from outside but consumed within the territory. This kind of terminal measurement neglects the external effect such as trade [16–19], which couldn't fully reflect an economy's total emissions. Thus, in this paper we adopt the embodied GHG emissions, which combine the direct emissions and the indirect emissions, to calculate the decoupling indicators. Secondly, the previous studies evaluated the decoupling indicators in some important sectors such as energy and transport. However, no decoupling research based on the GHG emissions emitted by the whole economy of a city or a country has yet been found. Thirdly, there is a dearth of city-level decoupling analysis as cities account for 67% of energy consumption worldwide and contribute 75% of the current global GHG emissions [20,21].

Macao, one of the two SARs (special administrative regions) of China, is located at the south-east coast of mainland China. With a population of 607,500 and an area of 30.3 km^2, Macao is supposed to be among the most densely populated regions in the world [22]. Known as one of the world's largest gaming centers, its economy heavily depends on tourism and gambling, light industry as well as external trade. The resources are scarce in Macao and there is almost no indigenous source of energy, making Macao a one hundred percent net energy importer. Since 2008, the United Nations formally announced that the Kyoto Protocol applied to Macao, which indicates that Macao has been an individual member to undertake the due obligations of GHG emissions mitigation. Therefore, Macao has to face the tremendous pressure on energy conservation and GHG abatement. As a consequence, it's urgent for Macao to decouple its GHG emissions from economic growth to ease the pressure.

This paper aims to capture a holistic picture of decoupling indicators of energy-related embodied GHG emissions (EEGE), TEC, total embodied GHG emissions (TEGE) with economic growth in Macao from 2000 to 2013, based on the most recent database. Of particular note is that the foundation of this paper is built on the previous works from Chen and his fellows [23–28]. On one hand, to our knowledge, this paper is the first decoupling study on Macao's TEC as well as TEGE with its economic growth, which also serves as a good supplement for city-level decoupling analysis. On the other hand, according to previous research on Macao carried out by Chen and his fellows [23–28], it is urgent for Macao to find effective and efficient ways to coordinate the relationship between GHG emissions and economic growth in order to achieve sustainable development. As a result, this paper provides support for Macao to evaluate its decoupling degrees as well as formulate energy conservation and emission mitigation policies.

The remainder of this paper is organized as follows: methodology and data adopted in this paper are elaborated in Section 2; Section 3 delineates a review of Macao's energy consumption and economic growth, while Section 4 presents the results and detailed analyses; some discussions are illustrated in Section 5; finally, conclusions are drawn in Section 6.

2. Methodology and data sources

2.1. Total embodied GHG emissions

World Resources Institute and the World Business Council for Sustainable Development (WRI/WBCSD) defined 3 scopes to benchmark a specific city's GHG emissions accounting. Scope 1 includes direct GHG emissions occurring from sources that are owned or controlled by the city such as fuel combustion, industrial process and fugitive emissions. Scope 2 accounts for indirect GHG emissions from purchased electricity consumed within the city. Other indirect emissions embodied in sources not produced by the city but attributable to the city are defined as Scope 3 [29]. Based on the embodied energy and GHG emissions databases built by Chen and his fellows [30–36], this paper calculates three major GHG emissions as carbon dioxide(CO_2), methane(CH_4) and nitrous oxide(N_2O) under 3 scopes and presents in CO_2 equivalent(CO_2 e.) by applying global warming potential(GWP), in the ratio 1:21:310 for CO_2:CH_4:N_2O [37]. TEGE can be calculated as:

$$TEGE = EGE_{trade} + DE \tag{1}$$

where EGE_{Trade} stands for the emissions embodied in external trade balance. DE represents direct emissions.

According to WRI/WBCSD, direct GHG emissions are principally the results of local electricity generation, physical or chemical processing, transportation and fugitive emission [29]. The GHG emissions from local electricity generation and transportation can be classified together into fuel combustion emissions, which can

Table 1
GHG emission factors of different furl types.

fuel energy	Direct emission factors				Indirect emission factors
	CO_2[a] Unit: kg/Tj	CH_4[a]	N_2O[a]	GWP[b] Unit: t CO_2 e./Tj	GWP[c] Unit: t CO_2 e./Tj
Gasoline	69,300	3	0.6	69.5	10.7
Kerosene	71,900	3	0.6	72.1	12.7
Gas oil & diesel	74,100	3	0.6	74.3	10.7
Fuel oil	77,400	3	0.6	77.6	10.1
Liquefied petroleum gas	63,100	1	0.1	63.2	11.0
Traditional fuels	112,000	1	1.5	112.5	77.9
Natural gas	56,100	1	0.1	56.2	20.9

[a] *Source*: IPCC [37].
[b] *Source*: Calculated by applying GWP based on the ratio given by IPCC [37].
[c] *Source*: Derived from Li [51].

be included in the GHG emissions embodied in external trade balance as Macao's fuel energy are all imported. As for physical or chemical processing, only cement and waste processing exist in Macao, when we take cement, aluminum, adipic acid, ammonia manufacture, and waste processing into consideration. With regard to fugitive emissions, equipment leaks, energy extraction and fossil fuel evaporation can be all neglected in Macao. In view of the above boundary defining, the calculation of DE only needs to take cement manufacture and waste processing into account.

2.2. Accounting process

2.2.1. Energy consumption

Embodied GHG emissions ascribed to fuel combustion depend on:

$$EGE_{energy} = \sum_i EC_i \times EF_i \tag{2}$$

where EC_i represents energy consumption by energy type i, which can be derived from *Yearbook of Statistic* [22,38–50]. EF_i stands for embodied emission factor with direct and indirect emission considered for each energy type i.

Direct emission factors of fuel energy are derived from IPCC [37], meanwhile, indirect emission factors of fuel energy are on the strength of previous studied which have constructed some helpful GHG emission data applicable on many aspects [30,32,51]. Ultimately, both direct and indirect emission factors of fuel energy are listed in Table 1.

In order to meet Macao's increasing electricity requirement and maintain favorable environment, Macao has purchased electricity from Guangdong Power Grid in ever-increasing quantities according to *CEM Annual Report* [52–65]. As the fuel mix and technology of imported electricity have changed over the accounting period, here we adopt different emission factor in different year, which can be updated by using:

$$EF_{im,n} = EF_{im,2007} \times \frac{I_n}{I_{2007}} \tag{3}$$

where $EF_{im,n}$ is the embodied GHG emission factor of electricity imported from mainland China in the year n. $EF_{im,2007}$ is the embodied GHG emission factor in 2007, calculated based on Chinese input-output table in 2007 [30]. I_n/I_{2007} is the ratio of GHG intensity in the year n compared to that of 2007. I_n can be derived from previous studies [66–73]. Table 2 presents the embodied emission factor of imported electricity from 2000 to 2013.

Table 2
GHG emission factor of imported electricity from 2000 to 2013 (Unit: t CO_2/Tj).

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
$EF_{im,n}$ [a]	236	231	229	223	226	227	223	217	228	213	208	202	199	197

[a] *Source*: Calculated by authors based on Eq. (3).

2.2.2. Cement manufacture

As for cement, here we combine direct emission and indirect emission embodied in trade balance together just for convenience, where indirect emission lies in cement manufactured out of Macao but consumed in Macao. So embodied GHG emissions from cement manufacture can be calculated as:

$$EGE_{cement} = CC \times CF \times EF_{clinker} \quad (4)$$

where *CC* is the amount of cement consumption (manufactured in Macao plus cement trade balance), which can be deprived from *Yearbook of Statistics* [22,38–50]. *CF* represents clinker fraction, which can be assumed as an overall value of 75% acceptably within good practice, while $EF_{clinker}$ is the emission factor of cement clinker with a value of 0.52 t CO_2/t clinker, according to IPCC [37].

2.2.3. Waste processing

Waste processing compromises municipal solid waste (MSW) treatment and waste water treatment in Macao.

(1) Macao has applied incineration for MSW treatment, so we can use the incineration plant electricity data to calculate the GHG emission of MSW treatment

$$EGE_{MSW} = E_{inci} \times EF_{inci} \quad (5)$$

where E_{inci} indicates electricity from incineration and the data can be achieved from *CEM Annual Report* [52–65]. EF_{inci} is emission factor of incineration of MSW, which is 0.7880 kg CO_2 e/kW·h obtained from [74].

(2) As for waste water treatment, CO_2 is not considered on account of its biogenic origin [37]. In addition, N content of Macao's waste water is not accessible. As a consequence, here we only take CH_4 into account. According to IPCC [37], the GHG emission from waste water treatment can be calculated using the following equation

$$EGE_{wastewater} = TOW \times EF_{BOD} \times 21 \quad (6)$$

where *TOW* is total organics in waste water in inventory year, while EF_{BOD} stands for emission factor with a recommended value of 0.6 kg CH_4/kg BOD. *21* is the ratio of GWP for CH_4:CO_2. To be more specific, *TOW* is measured as:

$$TOW = P \times Q_{BOD} \times 365 \quad (7)$$

where *P* represents population in inventory year, which is captured from *Yearbook of Statistics* [22,38–50]. Q_{BOD} is on behalf of the quantity of BOD per capita in inventory year, which is 0.04 t BOD/person/day, in the light of IPCC [37].

2.2.4. Trade balance

Imports and exports are divided into two primary categories in this paper in accordance with the available database: imports from/exports to mainland China and the rest of the world. Appendix Tables A1 and A2 demonstrate the goods and services imported/exported, which are taken from *Yearbook of Statistics* [22,38–50]. In Appendix Table A1, No. 1–40 are non-commodities, No. 41–49 are services and No. 50–56 are energy commodities. Meanwhile, the corresponding embodied emission factors of different commodities and services from/to different regions are shown in Appendix Tables A3 and A4, according to [30,32]. GHG embodied in trade balance can be calculated as:

$$EGE_{Trade} = EGE_{im} - EGE_{ex} = \sum_i Q_{i,im} \times EF_{i,im} - \sum_j Q_{j,ex} \times EF_{j,ex} \quad (8)$$

where $Q_{i,\,im}$ is Macao's import of item *i*, while $EF_{i,\,im}$ is the GHG emission factor of imported item *i*. Analogously, $Q_{j,\,ex}$ represents Macao's export of item *j*, while $EF_{j,\,ex}$ represents GHG emission factor of exported item *j*.

2.3. Decoupling index

According to the definition illustrated by Tapio [11] and the refinement described in Section 1, decoupling index can be measured as the ratio of the percentage change of the accounting target to the percentage change of the driving force from a base year to a target year, as displayed in the following equation:

$$DI_{T-B} = \frac{\Delta C_{T-B}\%}{\Delta GDP_{T-B}\%} \quad (9)$$

where DI_{T-B} is the decoupling index during the period from a base year *B* to a target year *T*. $\Delta C_{T-B}\%$ represents the percentage change of the accounting target such as EEGE, per capita TEC and per capita TEGE, which can be calculated as:

$$\Delta C_{T-B}\% = (C_T - C_B) / C_B \times 100\% \quad (10)$$

$\Delta GDP_{T-B}\%$ is the percentage change of GDP per capita, which is:

$$\Delta GDP_{T-B}\% = (GDP_T - GDP_B)/GDP_B \times 100\% \quad (11)$$

Eight logical possibilities can be distinguished as:

(1) $DI > 1.2$, $\Delta C\% > 0$, $\Delta GDP\% > 0$, expansive negative decoupling.
(2) $0.8 < DI < 1.2$, $\Delta C\% > 0$, $\Delta GDP\% > 0$, expansive coupling.
(3) $0 < DI < 0.8$, $\Delta C\% > 0$, $\Delta GDP\% > 0$, weak decoupling.
(4) $DI < 0$, $\Delta C\% < 0$, $\Delta GDP\% > 0$, strong decoupling.
(5) $DI > 1.2$, $\Delta C\% < 0$, $\Delta GDP\% < 0$, recessive decoupling.
(6) $0.8 < DI < 1.2$, $\Delta C\% < 0$, $\Delta GDP\% < 0$, recessive coupling.
(7) $0 < DI < 0.8$, $\Delta C\% < 0$, $\Delta GDP\% < 0$, weak negative decoupling.
(8) $DI < 0$, $\Delta C\% > 0$, $\Delta GDP\% < 0$, strong negative decoupling.

3. Review of Macao's energy consumption and economic growth 2000–2013

3.1. Macao's Gross Domestic Product (GDP)

Since the handover of the Macao's sovereignty to China in 1999, Macao has stepped into a new era of development and witnessed

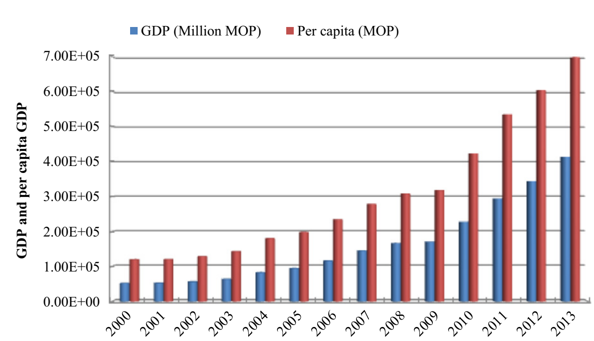

Fig. 1. Macao's GDP and per capita GDP 2000–2013.

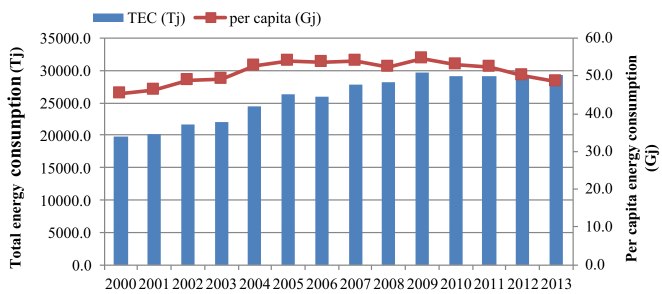

Fig. 2. Total energy consumption and per capita consumption.

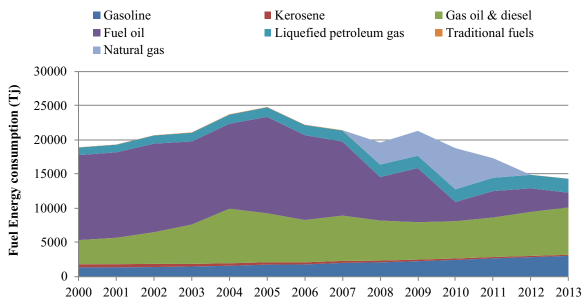

Fig. 3. Fuel energy consumption.

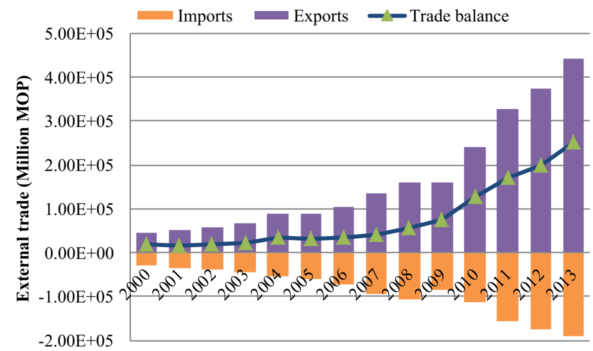

Fig. 5. External trade.

rapid economic growth under the policy of "one country, two systems". Most striking of all, Macao ranks the highest of the GDP per capita by PPP (purchasing power parity) in 2013, which is 142,599 US dollars, increased by 348.75% compared with that in 2000, according to World Bank [75]. Resulting from the "Legal Framework for the Operations of Casino Games of Fortune" in 2001 [76], Macao was crowned as the world's largest gaming center in 2006 [77]. Macao's GDP and per capita GDP (at current prices) have the same trend of variability from 2000 to 2013, which are portrayed in Fig. 1. Macao's per capita GDP in 2013 was 697,502 Pataca, which is equivalent to 87,306 US dollars (USD), approximately 5.8 times compared with per capita GDP in 2000. With the Closer Economic Partnership Arrangement, the Free Trade Policy and the Individual Visit Scheme (IVS), Macao's per capita GDP has acquired an average annual growth rate of 14.5% from 2000 to 2013.

3.2. *Macao's energy consumption*

The fast pace of the economic growth inevitably drives rapid increase in energy consumption. Generally, Macao's TEC and per capita energy consumption have gradually increased since its sovereignty was transferred to China, owing to the gaming industry and tourism boom. The opening of gambling right in 2002 and the implementation of mainland China's "Individual Visit Scheme" in 2003 have stimulated the emergence of massive buildings of casinos, restaurants and shopping malls as well as expanded the transport industry, resulting in huge electricity consumption from buildings and fuel oil consumption from vehicles, respectively. As depicted in Fig. 2, Macao's TEC reached a high value of 29,619.4 Terajoules (Tj) in 2009, increasing by 49.44% over the year 2000. However, the total energy used by Macao slightly went down from 2009 to 2013. From the per capita point of view, the trend of per capita energy consumption is similar to that of TEC, increased from 45.3 Gigajoules (Gj) per capita in 2000–54.6 Gj per capita in 2009, and finally dropped to 48.4 Gj per capita in 2013.

Fig. 3 expounds on Macao's fuel energy consumption structure. The total fuel energy consumption had an inverted-U trend as it first rose from 18923 Tj in 2000–24824 Tj in 2005, then dropped to 14319 Tj in 2013. Fuel oil had the largest share from 2000 to 2009, most of which was used for local generation. After its consumption peaked at 14117 Tj in 2005, its use saw annual reduction and sharply declined to 2156 Tj in 2013, mainly because imported electricity has increased rapidly since 2005 as shown in Fig. 4. To further optimize the energy consumption structure, Macao has imported natural gas from mainland China as an alternative since 2008 to replace fuel oil and diesel used by local electricity generation for its relatively low emissions of air pollutants.

As depicted in Fig. 4, total electricity consumption increased persistently from 1726.8 GWh in 2000–4409.0 GWh in 2013, with an average annual growth rate of 7.48%. Local electricity generated from fuel combustion varied significantly between 222 GWh and 1913.9 GWh. The amount of electricity from MSW incineration accounted for only 2–3% of the total electricity consumption. According to *CEM Annual Report* [52–65], Macao has purchased electricity from mainland China in ever-increasing quantities to meet Macao's rising electricity requirement. Imported electricity has soared since 2005 and dominated Macao's electricity consumption since 2007, which represented 92.06% of the total electricity consumption in 2013.

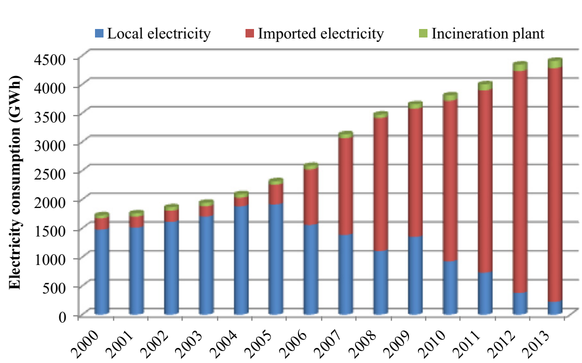

Fig. 4. Electricity energy consumption.

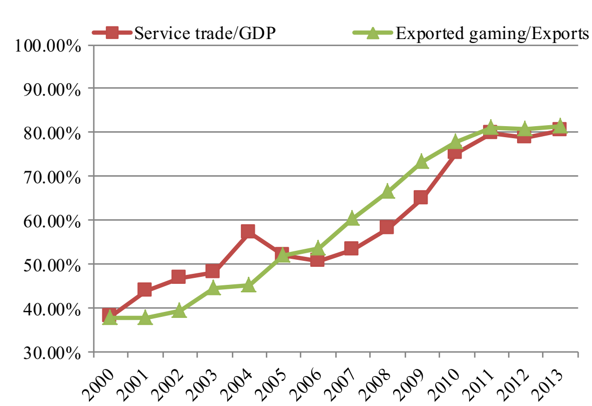

Fig. 6. The proportions of service trade/GDP and gaming/exports.

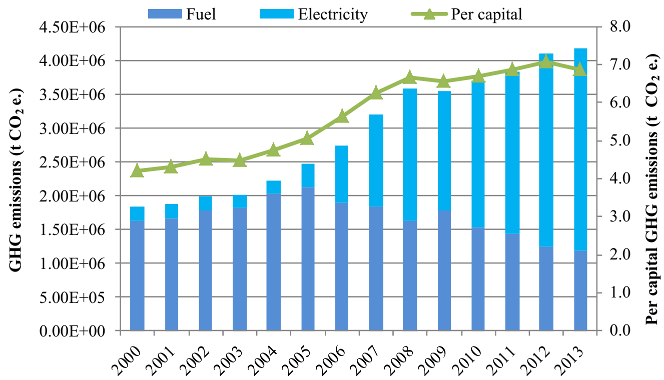

Fig. 7. Energy-related embodied GHG emissions.

3.3. *Macao's external trade*

As an individual member of the World Trade Organization, Macao has maintained good trade relationships with many countries and regions. During the period concerned, Macao's imports and exports both increased steadily, implying the average annual growth rates of 15.6% and 18.9%, as shown in Fig. 5. The decreases in 2009 are believed to be caused by the global economic crisis. The trade balance increased by 234,332.47 Million MOP, from 17622.13 Million MOP in 2000 to 251,954.60 Million MOP in 2013. As discussed in Section 2.2.4, the external trade covers not only goods, but also services. Service trade has become more and more prosperous as a result of the booming gaming-related tourism in recent years. As presented in Fig. 6, service trade is playing a more important role in Macao's economy. The proportion of service trade in the GDP rose from 38.07% in 2000 to 80.61% in 2013, while the proportion of exported gaming in exports increased from 37.68–81.28%.

4. Results

4.1. *Embodied GHG emissions*

4.1.1. *GHG emissions embodied in energy consumption*

As presented in Fig. 7, total GHG emissions embodied in Macao's energy consumption more than doubled during the accounting period, growing from 1.84E+06 t CO_2 e. in 2000 to 4.18E+06 t CO_2 e. in 2013, along with the simultaneously increasing TEC (see Fig. 2). The trend of per capita GHG emissions was similar to that of total GHG emissions except for the year of 2013. The per capita GHG emissions embodied in energy consumption increased from 4.21 t CO_2 e. in 2000–6.87 t CO_2 e. in 2013. However, GHG emissions saw a decline in 2009. The total GHG emissions' growth rate decelerated in 2013, while the population continued to grow, leading to the decrease in per capita GHG emissions.

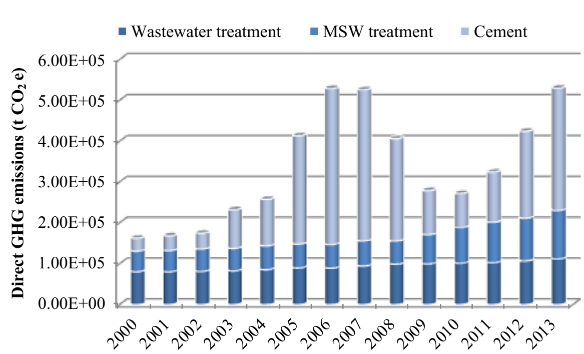

Fig. 8. Direct GHG emissions.

Table 3
GHG emissions embodied in external trade (t CO_2 e.).

Year	EGE_{im}	EGE_{ex}	EGE_{trade}
2000	5.03E+06	2.07E+06	2.96E+06
2001	5.25E+06	2.25E+06	2.99E+06
2002	5.45E+06	2.72E+06	2.73E+06
2003	5.87E+06	2.93E+06	2.94E+06
2004	7.07E+06	3.74E+06	3.33E+06
2005	8.06E+06	4.05E+06	4.01E+06
2006	9.75E+06	4.78E+06	4.97E+06
2007	1.09E+07	5.92E+06	5.00E+06
2008	1.08E+07	6.37E+06	4.44E+06
2009	9.25E+06	6.33E+06	2.91E+06
2010	1.08E+07	9.43E+06	1.38E+06
2011	1.39E+07	1.29E+07	1.01E+06
2012	1.58E+07	1.46E+07	1.16E+06
2013	1.73E+07	1.71E+07	2.49E+05

4.1.2. *Direct GHG emissions*

Fig. 8 describes the trend of direct emissions in Macao from 2000 to 2013, which changed within a narrow range between 1.62E+5 t CO_2 e. and 5.30E+5 t CO_2 e. Cement manufacture, mainly driven by various large-scale tourism and gaming projects, dominated the variation of direct GHG emissions. Propelled by the growing population, the amount of wastewater and MSW processed grew modestly during the accounting period.

4.1.3. *GHG emissions embodied in trade balance*

Embodied GHG emissions in trade balance are summarized in Table 3. The trend of embodied GHG emissions in EGE_{im} and EGE_{ex} was similar to that of external trade's monetary value, as described in Section 3.3. Macao avoided emitting 5.03E+06–1.73E+07 t CO_2 e. by consuming imported goods and services from 2000 to 2013. Due to the increasing proportion of gaming service in exports (see Fig. 6), the GHG emissions embodied in exports increased by 1.50E+07 t CO_2 e., from 2.07E+06 t CO_2 e. to 1.71E+07 t CO_2 e. during the period concerned.

Based on EGE_{im} and EGE_{ex}, EGE_{trade} is also revealed in Table 3. Although the monetary value of exports far exceeded that of imports, it's obvious that EGE_{ex} was less than EGE_{im} during the accounting period, which can be explained by the high GHG emission intensity of imported goods and low GHG emission intensity of exported services.

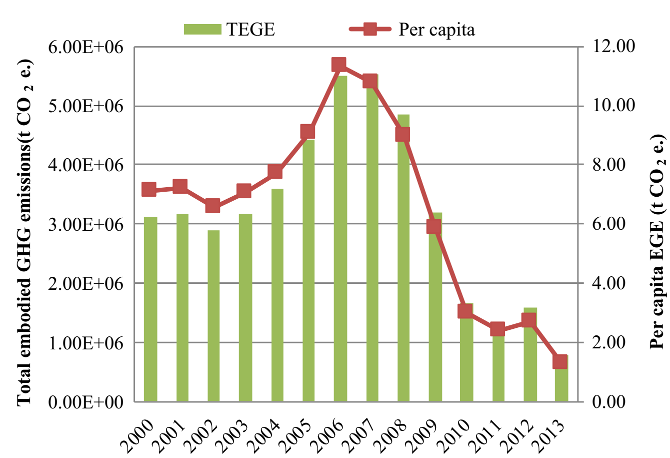

Fig. 9. Total and per capita embodied GHG emissions.

Table 4
The decoupling analysis of EEGE from economic growth.

Year	ΔEEGE%	ΔGDP%	DI	Decoupling state
2000 – 2001	0.0204	0.0054	3.80	Expansive negative decoupling
2001 – 2002	0.0510	0.0653	0.78	Weak decoupling
2002 – 2003	−0.0063	0.1123	−0.06	Strong decoupling
2003 – 2004	0.0617	0.2608	0.24	Weak decoupling
2004 – 2005	0.0613	0.1016	0.60	Weak decoupling
2005 – 2006	0.1180	0.1800	0.66	Weak decoupling
2006 – 2007	0.1054	0.1897	0.56	Weak decoupling
2007 – 2008	0.0662	0.1055	0.63	Weak decoupling
2008 – 2009	−0.0153	0.0314	−0.49	Strong decoupling
2009 – 2010	0.0218	0.3309	0.07	Weak decoupling
2010 – 2011	0.0258	0.2652	0.10	Weak decoupling
2011 – 2012	0.0272	0.1286	0.21	Weak decoupling
2012 – 2013	−0.0258	0.1558	−0.17	Strong decoupling

4.1.4. Total and per capita embodied GHG emissions

With the integration of EGE_{trade} and DE, the embodied GHG emissions induced by Macao during 2000–2013 are portrayed in Fig. 9. The total embodied GHG emissions were 3.13E+06 t CO_2 e. in 2000, then hit a trough at 2.90E+06 t CO_2 e. in 2002, and five years later the emissions soared and exceeded the level of 2002 by 90%, reaching the pinnacle at 5.53E+06 t CO_2 e. in 2007. However, emissions began to plummet in the following six years and significantly dropped into7.79E+05 t CO_2 e. in 2013. It can be explained by the continuously increasing exports of service trade, owing to the booming gaming industry as presented in Section 3.3. Macao's economy is so small and heavily relies on external trade that its economy is susceptible to external economic situation and local consumption. Thus it is not surprising to find out that Macao's total embodied GHG emissions varied widely from year to year.

Per capita embodied GHG emissions also varied in the accounting period, with the same trend of TEGE. Fig. 9 indicated that per capita emissions peaked at 1.14E+01 t CO_2 e. in 2006 while that of 2013 was the lowest, with a value of 1.28E+00 t CO_2 e.

4.2. Decoupling analyses

According to the method illustrated in Section 2.3, the decoupling indicators of EEGE, TEC and TEGE from economic growth are presented in this section.

4.2.1. GHG emissions embodied in energy consumption

The decoupling states of EEGE from economic growth are described in Table 4. The change rates in per capital GDP were all positive over 2000–2013, and the change rates in per capital EEGE were also positive except for 2003, 2009 and 2013. Thus it performed strong decoupling in 2003, 2009 and 2013, which are the optimal state of decoupling, and the decoupling indictors were −0.06, −0.49 and −0.17, respectively. Expansive negative decoupling only appeared in 2001 with a decoupling indicator of 3.80, namely, the growth rate of per capital EEGE is much higher than that of per capital GDP, which indicated that the decoupling state in 2001 was unfavorable. In the most of the accounting years, they were in the state of weak decoupling with the decoupling indicators ranging from 0.07 to 0.78, which manifested that the decoupling states are desirable.

Table 5
The decoupling analysis of TEC from economic growth.

Year	ΔTEC%	ΔGDP%	DI	Decoupling state
2000 – 2001	0.0237	0.0054	4.41	Expansive negative decoupling
2001 – 2002	0.0557	0.0653	0.85	Expansive coupling
2002 – 2003	0.0014	0.1123	0.01	Weak decoupling
2003 – 2004	0.0757	0.2608	0.29	Weak decoupling
2004 – 2005	0.0217	0.1016	0.21	Weak decoupling
2005 – 2006	−0.0056	0.1800	−0.03	Strong decoupling
2006 – 2007	0.0089	0.1897	0.05	Weak decoupling
2007 – 2008	−0.0314	0.1055	−0.30	Strong decoupling
2008 – 2009	0.0443	0.0314	1.41	Expansive negative decoupling
2009 – 2010	−0.0335	0.3309	−0.10	Strong decoupling
2010 – 2011	−0.0110	0.2652	−0.04	Strong decoupling
2011 – 2012	−0.0402	0.1286	−0.31	Strong decoupling
2012 – 2013	−0.0346	0.1558	−0.22	Strong decoupling

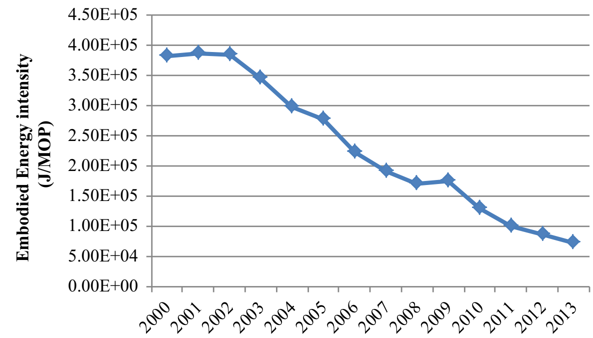

Fig. 10. Embodied energy intensity in Macao 2000–2013.

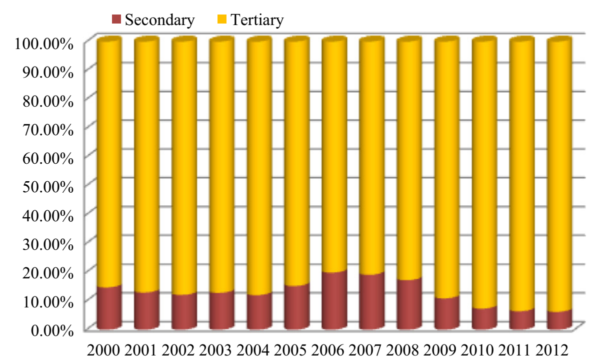

Fig. 11. Industry structure in Macao.

4.2.2. Total energy consumption

Table 5 lists the decoupling states for the TEC. The TEC presented expansive negative decoupling with GDP growth in 2001 and 2009, and decoupling indicators were 4.41 and 1.41, respectively. It performed expansive coupling in 2002 with the decoupling indicator of 0.85. However, the weak or strong decoupling occurred in the rest years of the accounting period.

Several complicated factors have effect on the decoupling indicators of TEC from economic growth. The most important three factors are energy intensity, industrial structure and energy consumption structure. The energy intensity from 2000 to 2013 is delineated in Fig. 10. There is a continual decrease in energy intensity from 3.83E+05 J/MOP in 2000 to 7.11E+04 J/MOP in 2013. The year of 2001 and 2009 with the expansive negative decoupling state, however, see an increase in energy intensity, which implies that the energy intensity has a negative effect on decoupling. Fig. 11 demonstrates the industry structure in Macao. Along with the expansion of urbanization, there is no longer any primary industry in Macao. Tertiary industry has become the backbone of Macao's economy, contributing over 80% of its GDP.

4.2.3. Total embodied GHG emissions

The decoupling results for TEGE are summarized in Table 6. In general, Macao is approaching the sustainable development gradually from the perspective of decoupling indicator. Since 2000,

Table 6
The decoupling analysis of TEGE from economic growth.

Year	ΔTEGE%	ΔGDP%	DI	Decoupling state	Decoupling trend
2000 – 2001	0.0147	0.0054	2.74	Expansive negative decoupling	Expansive negative decoupling
2001 – 2002	−0.0917	0.0653	−1.40	Strong decoupling	Weak decoupling
2002 – 2003	0.0748	0.1123	0.67	Weak decoupling	
2003 – 2004	0.0910	0.2608	0.35	Weak decoupling	
2004 – 2005	0.1758	0.1016	1.73	Expansive negative decoupling	Expansive negative decoupling
2005 – 2006	0.2523	0.1800	1.40	Expansive negative decoupling	
2006 – 2007	−0.0515	0.1897	−0.27	Strong decoupling	Strong decoupling
2007 – 2008	−0.1645	0.1055	−1.56	Strong decoupling	
2008 – 2009	−0.3456	0.0314	−11.02	Strong decoupling	
2009 – 2010	−0.4910	0.3309	−1.48	Strong decoupling	
2010 – 2011	−0.1984	0.2652	−0.75	Strong decoupling	
2011 – 2012	0.1296	0.1286	1.01	Expansive coupling	
2012 – 2013	−0.5278	0.1558	−3.39	Strong decoupling	

Table 7
Decoupling analysis in other countries/regions.

Countries/Regions	Decoupling term	Time period	Decoupling state
Jiangsu[15]	CO_2 emissions- economic growth	2008 – 2009	weak decoupling
Qatar[81]	CO_2 emissions- economic growth	2010 – 2011	absolute decoupling
Saudi Arabia[81]	CO_2 emissions- economic growth	2010 – 2011	absolute decoupling
Brazil[13]	CO_2 emissions- economic growth	2008 – 2009	absolute decoupling
Italy[82]	energy consumption-economic growth	2002 – 2006	coupling
Beijing-Tianjin -Hebei Region [83]	carbon emissions- industry development	2009 – 2010	weak decoupling

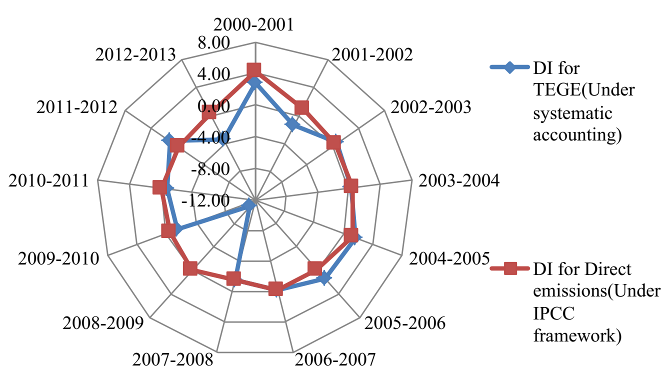

Fig. 12. DI for TEGE and DI for direct emissions.

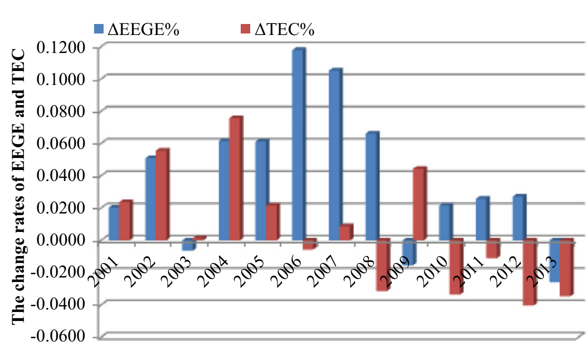

Fig. 13. The change rates of EEGE and TEC.

Macao's whole economy has witnessed a distinct tendency toward decoupling, shifting from the expansive negative decoupling in 2001 to weak decoupling in 2002–2004, followed by a short-term expansive negative decoupling in 2005–2006 and then a long period of strong decoupling in 2007–2013.

The results suggest that the regulations put in place to rein in emissions are starting to have an impact. Since 2008, the time when Macao submitted its ratification of Kyoto Protocol, Macao has launched a series of plans that are beneficial to its sustainable development. To optimize the energy structure, Macao introduced natural gas, which has comparatively low emission factor, as an alternative energy of gas oil & diesel for electricity generation from 2008 [57]. Furthermore, since 2012, Macao gradually widened the nature gas' range of application. Besides for electricity generation, natural gas is also used for transportation and household [78]. In September 2012, Macao Environmental Protection Agency published *Macao's Environmental Protection Conceptual Planning (2010–2020)*, which systematically depicted the roadmap for sustainable development [79]. Given this, all the efforts Macao has made to maintain sustainable development should be kept on.

Decoupling states of energy consumption-economic growth and GHG emissions-economic growth are also compared with those of other countries/regions in recent years, presented in Table 7. The decoupling states varied in different countries/regions when different time period was accounted. Thus, it's of great significance to draw a holistic picture of the evolving of decoupling states for a country/region. The results in Table 7 were obtained in terms of production-based emissions, while our study was carried out with both production-based emissions and consumption-based emissions.

5. Discussions

Decoupling indicators for Macao, where sustainable development should be achieved imminently, are crucial for policy-makers to evaluate the extent of sustainable development and thus to identify comprehensive energy conservation and GHG mitigation strategies.

From the systematic perspective, the current decoupling studies based on the direct GHG emissions are no longer sufficient to capture a holistic picture of theoretical framework for decoupling, because the direct accounting theory under IPCC framework emphasizes on the producer, leading to considerable GHG leakage. As Macao relies heavily on goods and electricity produced outside the city boundary, direct accounting will cause serious GHG leakage problem. Fig. 12 compares the decoupling indicators of TEGE in terms of systematic accounting with that of direct accounting. The differences reflect that the application of different accounting method of GHG emissions will have distinct effects on the corresponding decoupling indicators. For instance, it experienced expansive negative decoupling in 2006 with the decoupling indicator of 1.40 calculating based on the embodied GHG emissions. Correspondingly, strong decoupling occurred in 2006 and the decoupling indicator was −0.20 calculated in light of direct GHG emissions. It's obvious that, under some circumstances, decoupling indicators on account of direct emissions may mislead the administrators and policy makers to have a positive expectation for current policies. Therefore, it's urgent for Macao to adjust its policies under the viewpoint of systems analysis.

Table 5 indicates that Macao's energy consumption has decoupled from economic growth. However, some underlying issues can be revealed when comparing the change rates of EEGE with that of TEC. As depicted in Fig. 13, the change rates of EEGE coupled with that of TEC in 2001–2004 and 2013. Worse still, the change rates of EEGE have exceeded that of TEC by far in 2005–2008 and 2010–2012, the last phenomenon expected to be seen. It can be explained by the increasing average emission intensity of energy consumed by Macao in those undesirable years. One feasible measure is to optimize the energy structure and promote renewable energy. As verified by Office for the Development of the Energy Sector of the Macao Special Administrative Region, Macao has a considerable solar energy resource, amounting to an annual global solar radiation of 5000MJ/m^2 with significant potential value of exploitation [80]. By utilizing the solar energy, Macao could not only reduce its dependence on imported energy, but also cut down GHG emissions embodied in massive imported electricity.

6. Conclusions

A comprehensive framework of embodied GHG emissions induced by Macao and its relevant decoupling analysis in terms of decoupling indicator proposed by Tapio is presented in this paper. This study is the first attempt to examine the occurrence of a decoupling between the economic growth and energy-related GHG emissions, TEC as well as TEGE from 2000 to 2013 in Macao based on the systematic accounting theory.

Macao's TEGE witnessed a significant fluctuation from 2000 to 2013, rising from 3.13E+06 t CO_2 e. in 2000 to 5.53E+06 t CO_2 e. in 2007, then plummeting into 7.79E+05 t CO_2 e. in 2013. Our results also show that indirect emissions dominated Macao's TEGE. During the study period, the whole Macao economy has experienced four decoupling stages: expansive negative decoupling (2001), weak decoupling (2002–2004), expansive negative decoupling (2005–2006) and strong decoupling (2007–2013), with a distinct tendency towards strong decoupling. When comparing the decoupling indicators under systematic accounting and direct accounting, many differences can be seen, which may misguide the policy makers.

Our results prove that Macao's TEC has decoupled from its economic growth, indicating that Macao's economic growth is becoming less reliable on energy consumption. The EEGE, however, strongly coupled with TEC because of the increasing average emission intensity of energy consumed by Macao. To optimizing the energy structure is an effective way to tackle with the issue.

With the help of decoupling results under the viewpoint of systems analysis, energy-saving and emission mitigation measures can be devised for Macao, which would help Macao maintain sustainable development. For those urban economies with similar characteristics such as heavy dependence on imports with Macao, the present study is also applicable to their decoupling analysis for embodied GHG emissions and can provide insights into emission control and energy saving.

Acknowledgement

This research was supported by the National Natural Science Foundation of China (Grant Nos. 51306067 and 11272012) and the Fundamental Research Funds for the Central Universities (Nos. 2016YXZD007 and 2016YXMS043).

Appendix A

See: Tables A1–A4.

Table A1
Inventory of imports.

No.	Item[a]
1	Live animals other than animals of division 03
2	Meat and meat preparations
3	Fish (not marine mammals), crustaceans, molluscs and aquatic invertebrates and preparations thereof
4	Cereals and cereal preparations
5	Vegetables and fruit
6	Coffee, tea, cocoa, spices and manufactures thereof
7	Feeding stuff for animals (not including unmilled cereals)
8	Beverages
9	Fixed vegetable fats and oils, crude, refined or fractionated
10	Dairy products and birds' eggs
11	Miscellaneous edible products and preparations
12	Tobacco and tobacco manufactures
13	Medicinal and pharmaceutical products
14	Essential oils and resinoids and perfume materials; toilet, polishing and cleansing preparations
15	Plastics in primary forms
16	Rubber manufactures, n.e.s.
17	Paper, paperboard, and articles of paper pulp, of paper or of paperboard
18	Textile yarn, fabrics, made-up articles, n.e.s., and related products
19	Inorganic chemicals
20	Non-metallic mineral manufactures, n.e.s.
21	Iron and steel
22	Non-ferrous metals
23	Manufactures of metals, n.e.s.
24	General industrial machinery and equipment, n.e.s., and machine parts, n.e.s.
25	Power generating machinery and equipment
26	Machinery specialized for particular industries
27	Office machines and automatic data processing machines
28	Telecommunications and sound recording and reproducing apparatus and equipment
29	Electrical machinery, apparatus and appliances, n.e.s., and electrical parts thereof
30	Road vehicles (including air-cushion vehicles)
31	Other transport equipment
32	Prefabricated buildings; sanitary, plumbing, heating and lighting fixtures and fittings, n.e.s.
33	Articles of apparel and clothing accessories
34	Travel goods, handbags and similar containers
35	Footwear
36	Photographic apparatus, equipment and supplies and optical goods, n.e.s.; watches and clocks
37	Professional, scientific and controlling instruments and apparatus, n.e.s.
38	Miscellaneous manufactured articles, n.e.s.
39	Raw water
40	Sugars, sugar preparations and honey
41	Hotels and restaurants
42	Wholesale and retail trade; repairs
43	Land transport; transport via pipelines
44	Water transport
45	Air transport
46	Supporting and auxiliary transport activities; activities of travel agencies
47	Post and telecommunications
48	Finance and insurance
49	Other community, social and private services
50	Gasoline
51	Kerosene
52	Gas oil & diesel
53	Fuel oil
54	Liquefied petroleum gas
55	Natural gas
56	Electricity

[a] *Source*: *Yearbook of Statistics* [22,38–50].

Table A2
Inventory of exports.

No.	Item[a]
1	Garments
2	Textile fabrics
3	Textile yarn and thread
4	Textile raw material
5	Textile made-up articles and related products
6	Feathers, down and articles thereof
7	Toys
8	Raw Hides, skins and leather
9	Articles of apparel, clothing accessories and other articles of leather or fur skin
10	Optical instruments
11	Footwear
12	Travel goods, handbags and related products
13	Machinery and mechanical appliances
14	Radios, TV, image and sound recorders and reproducers
15	Electrical and electronic components and articles for electro-technical use
16	Furniture, incl. frames, cases, suitcases and similar articles
17	Watches and clocks
18	Copper and articles thereof
19	Tobacco and wine
20	Jewelry
21	Hotels and restaurants
22	Wholesale and retail trade; repairs
23	Land transport; transport via pipelines
24	Water transport
25	Air transport
26	Supporting and auxiliary transport activities; activities of travel agencies
27	Post and telecommunications
28	Finance and insurance
29	Other community, social and private services

[a] *Source*: *Yearbook of Statistics* [22,38–50].

Table A3
Embodied GHG emission factors of imports.

Item	**World**[a] **Unit: t CO_2/1E+06$**	**Mainland China**[b] **Unit: t CO_2/1E+04CNY**
1	2.83E+03	3.43E+00
2	1.17E+03	2.73E+00
3	1.17E+03	1.27E+00
4	1.17E+03	–[c]
5	2.83E+03	4.20E+00
6	1.17E+03	–
7	1.17E+03	–
8	1.17E+03	3.01E+00
9	1.17E+03	–
10	1.17E+03	–
11	1.17E+03	–
12	1.17E+03	1.20E+00
13	3.41E+02	–
14	1.29E+03	3.29E+00
15	1.29E+03	–
16	8.46E+02	–
17	4.70E+02	3.60E+00
18	6.78E+02	4.58E+00
19	1.29E+03	–
20	8.46E+02	1.12E+01
21	1.22E+03	1.18E+01
22	1.22E+03	4.84E+00
23	5.57E+02	–
24	5.01E+02	4.09E+00
25	5.01E+02	–
26	5.01E+02	–
27	1.79E+02	3.40E+00
28	3.74E+02	4.73E+00
29	3.95E+02	5.43E+00
30	4.39E+02	–
31	4.76E+02	–
32	6.23E+02	–
33	6.78E+02	3.48E+00
34	6.78E+02	–
35	6.78E+02	3.48E+00
36	5.01E+02	–
37	5.01E+02	–
38	3.04E+02	1.64E+00
39	–	3.60E+00
40	1.17E+03	3.28E+00
41	5.24E+02	2.52E+00
42	1.03E+03	1.09E+00
43	1.03E+03	2.46E+00
44	1.16E+03	2.71E+00
45	1.31E+03	3.60E+00
46	5.00E+02	1.67E+00
47	1.88E+02	1.73E+00
48	1.65E+02	4.61E−01
49	2.98E+02	2.43E+00

[a] Source: Chen and Chen [32].
[b] Source: Chen and Chen [30].
[c] No such imports.

Table A4
Embodied GHG emission factors of exports.

Item	**World**[a] **Unit: t CO2/1E+06$**	**Mainland China**[b] **Unit: t CO2/1E+04CNY**
1	–[c]	2.84E+00
2	–	4.58E+00
3	–	4.58E+00
4	–	4.58E+00
5	–	1.03E+00
6	–	2.60E+00
7	–	3.38E+00
8	–	2.60E+00
9	–	2.60E+00
10	8.46E+02	–
11	–	3.43E+00
12	6.78E+02	–
13	5.01E+02	–
14	3.74E+02	–
15	–	3.79E+00
16	–	9.18E+00
17	5.01E+02	–
18	5.57E+02	–
19	4.36E−01	–
20	5.85E−02	–
21	5.24E+02	–
22	1.03E+03	–
23	1.03E+03	–
24	1.16E+03	–
25	1.31E+03	–
26	5.00E+02	–
27	1.88E+02	–
28	1.65E+02	–
29	2.98E+02	–

[a] Source: Chen and Chen [32].
[b] Source: Chen and Chen [30].
[c] No such imports.

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