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Urban carbon dioxide equivalent (CO_2e) accounting based on the GPC framework

A case of the underdeveloped city of Nanchang, China

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Abstract

Purpose – This paper aims to provide a typical example of accounting for the carbon dioxide equivalent (CO_2e) in underdeveloped cities, especially for the Poyang Lake area in China. The accounting can increase public understanding and trust in climate mitigation strategies by showing more detailed data.

Design/methodology/approach – The paper uses the "Global Protocol for Community-scale greenhouse gas emission inventories (GPC)" method, a worldwide comparable framework for calculating urban CO_2e emission (CE). The empirical case is an underdeveloped city, Nanchang, in China.

Findings – The results show the total CE of Nanchang, containing the electricity CE of Scope 2, grew rapidly from 12.49 Mt in 1994 to 55.00 Mt in 2014, with the only recession caused by the global financial crisis in 2008. The biggest three contributors were industrial energy consumption, transportation and industrial processes, which contributed 44.71-72.06, 4.10-25.07 and 9.07-22.28 per cent, respectively, to the total CE.

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Almost always, more than 74.41 per cent of Nanchang's CE was related to coal. When considering only the CEs from coal, oil and gas, these CEs per unit area of Nanchang were always greater than those of China and the world. Similarly, these CEs per gross domestic product of Nanchang were always bigger than those of the world. Thus, based on these conclusions, some specific countermeasures were recommended.

Originality/value – This paper argues that the CO_2e accounting of underdeveloped cities by using the GPC framework should be promoted when designing climate mitigation policies. They can provide more scientific data to justify related countermeasures.

Keywords Accounting, Sustainable development, Carbon dioxide equivalent (CO_2e), CO_2e emission (CE), GPC, Low-carbon future

Paper type Research paper

1. Introduction

Currently, climate change is damaging the environment around us (Lin *et al.*, 2015), and cities have become the center of people's social-economic lives (Yu *et al.*, 2015). More than 3.6 billion people live in cities (Gouldson *et al.*, 2015), and urban population will exceed 6.7 billion in 2050 (UNDESA, 2014). With urbanization, more fuel will be used in cities, and greenhouse gases or carbon dioxide equivalent (CO_2e) will be increasingly emitted into the atmosphere, resulting in an acceleration of global warming (Wang *et al.*, 2015). If we do not take effective action, the average global temperature will increase approximately 5.8°C over the next 100 years. This possibility poses a major threat to global sustainable development (Ren *et al.*, 2015). The Intergovernmental Panel on Climate Change (IPCC) estimates that the fuels consumed within cities account for approximately 44 per cent of global CO_2e emissions (CE) (IPCC, 2014). When considering the final consumption of electricity, the emission shares of cities may reach approximately 71-76 per cent or even higher (Feng *et al.*, 2014; Hoornweg *et al.*, 2011; Satterthwaite, 2008). Therefore, to combat climate change, people have recently developed methods of accounting for cities' CEs to allow accurate recording through discussion of the related adaptive measures (Dodman, 2009).

These methods fall into three categories:

(1) bottom-up, which calculates the emissions of different sectors separately and adds them to obtain an overall result;

(2) top-down, which estimates the distributive value using the total national or regional emissions and some divided factors; and

(3) the hybrid method, in which some types of emissions may be counted using the bottom-up method and the rest using the top-down or other methods (Table I).

IPCC (2006) is a typical bottom-up method that divides emission sources into four sectors: energy; industrial processes and product use (IPPU); agriculture, forestry and other land use (AFOLU); and waste. However, the method is mainly suitable for and often used in national CE accounting (Guan *et al.*, 2012, 2014; Liu *et al.*, 2014, 2015; Wang *et al.*, 2014; Chen, 2015). Similarly, the Greenhouse Gas Protocol (WRI/WBCSD, 2004) is also bottom-up. It divides emissions into three scopes and is mainly suitable for corporate CE accounting (Ibrahima *et al.*, 2012). Subsequently, Kennedy *et al.* (2010) proposed a more specific accounting system with six sectors: electricity, heating and industrial fuels, ground transportation fuels, aviation and marine transportation, IPPU and waste (Kennedy *et al.*, 2009, 2014; Sugar *et al.*, 2012; Singh and Kennedy, 2015). Similarly, Bi *et al.* (2011) suggested another accounting framework. This framework also has six sectors but differs slightly from Kennedy's and is more suitable for calculating CEs in China's developed cities such as Nanjing (Wang *et al.*, 2012). In 2014, the

Table I.
Comparison of current major methodologies for urban CE accounting

Method	Author (year)	Category	Summary or assessment (distinguished by the marked sign "*")
The Greenhouse Gas Protocol	WRI/WBCSD (2004)	Bottom-up	Divided emissions into three scopes Several sectors: energy, metals, chemicals, minerals, waste, pulp and paper *mainly used in corporate CE accounting
IPCC	IPCC (2006)	Bottom-up	Provides guidance on emission factors, data and equation Four sectors: energy, IPPU, waste and AFOLU *mainly used in national CE accounting
Dhakal	Dhakal *et al.* (2010)	Top-down	Adopted energy use per unit GRP as a key indicator to estimate divided city CEs Emission factors were taken from IPCC, 2006
Kennedy	Kennedy *et al.* (2010)	Bottom-up	Adopted three scopes proposed by WRI/WBCSD Six sectors: electricity, transportation, IPPU and waste, etc.
Bi	Bi *et al.* (2011)	Bottom-up	Six sectors again, but different slightly from Kennedy *The earliest case addressing a developed city in China
Lin	Lin *et al.* (2013)	Hybrid	Calculated the emissions based on three scopes Scopes 1 and 2 were estimated using the IPCC (2006), and Scope 3 was calculated using life-cycle analysis
GPC	C40 *et al.* (2014)	Bottom-up	Contained three scopes and five sectors *Based on IPCC (2006), but more comprehensive, transparent and accurate and specifically suitable for cities
PAS 2070	BSI (2014)	Hybrid	Direct plus supply chain method was equal to GPC Consumption-based method used the IO models from a life-cycle perspective
Zhang	Zhang *et al.* (2015)	Top-down	Adopted 135-sector IO tables The others were the same as Dhakal

"Global protocol for community-scale greenhouse gas emission inventories (GPC)" was published by the ICLEI, World Resources Institute (WRI) and C40 (a network of the world's megacities committed to addressing climate change both locally and globally). This protocol provides a much more comprehensive, transparent and accurate set of guidelines than the described bottom-up methods such as the IPCC, 2006. Therefore, the GPC is considered to be a global framework that can provide comparable data for calculating urban CEs (C40 *et al.*, 2014).

Conversely, Dhakal (2009, 2010) adopted energy use per unit gross regional product (GRP) as a key indicator to estimate divided city CEs in China; this can be described as a top-down method. A similar, more detailed, top-down allocation approach using 135-sector input-output (IO) tables was also proposed (Zhang *et al.*, 2015). In addition, some hybrid methods have been suggested (Lin *et al.*, 2013; Paloheimo and Salmi, 2013; Zhang *et al.*, 2014; Ru *et al.*, 2015). For example, in 2014, the British Standards Institution (BSI, 2014) proposed two methods in its Publicly Available Specifications 2070. One method is called the direct plus supply chain method and could be considered equivalent to the GPC. The other uses the IO table taking the life-cycle perspective and is called the consumption-based method.

China, the world's largest developing country, has already become one of the top energy consumers and the top CO_2e emitter in the world (Chen and Lin, 2015; Yang *et al.*, 2015;

IEA, 2013; Liu *et al.*, 2013). China has committed to a series of targets to decrease CEs, e.g. decreasing the carbon intensity to 17 per cent below 2010 levels by the year 2015 and 40-45 per cent below 2005 levels by the year 2020 (Cong and Wei, 2010; Liu *et al.*, 2015). Academically, some benchmarks or methods of urban CE accounting (Ramaswami *et al.*, 2008; Finnveden *et al.*, 2009; Hillman and Ramaswami, 2010) that are suitable for developed cities in China such as Xiamen and Nanjing have also been published (Bi *et al.*, 2011; Lin *et al.*, 2013). However, these methods often cannot be used directly in other cities, especially in underdeveloped cities such as Nanchang, because of disparities in the statistical indexes or missing data. As the capital of Jiangxi Province in the central region of China, Nanchang is a typical underdeveloped city. To calculate this city's CEs, there is insufficient information for the top-down method, e.g. an IO table of energy use at the city scale, to complete the computation. Therefore, the most recent bottom-up method (the GPC framework) was used. First, the CEs in Nanchang were comprehensively calculated based on the available data. Then, some countermeasures for this city's low-carbon future and sustainable development were suggested after careful analysis. The remaining context is as follows. Detailed descriptions of the regional outline, CE accounting framework and data are given in Section 2. An analysis of the results and a discussion are presented in Section 3. Conclusions and specific suggestions of low-carbon strategies for this city are given in Section 4.

2. Methodology

2.1 Outline of the study area

The studied area, Nanchang, is located at 28° 09′-29° 11′ N and 115° 27′-116° 35′ E and has an administrative area of 7,402 km^2. In China's national project establishing the first low-carbon pilot cities in 2010, eight cities and five provinces were tasked to pursue a low-carbon economic transformation. Nanchang was one of these cities and was committed to taking efficient action to decrease its energy intensity and CEs. Nanchang has also been drawing increasing attention because of its special economic policies. For example, a comprehensive free trade area in Nanchang's "Airport Economic Zone" was approved in 2016. This policy increased the opportunities for Nanchang to transform its pattern of development. However, some fundamental information has not been identified in the public approach, such as an accounting framework or method for analyzing the urban CEs of Nanchang.

2.2 Stationary energy

As shown in Figure 1, the calculation sectors were classified into three scopes (Kennedy *et al.*, 2010). Scope 1 includes stationary and mobile fuel combustion occurring only within the urban geographical boundary. Based on Scope 1, Scope 2 contains the emissions associated with electricity used within the city boundary but generated outside it. Emissions from the life-cycle perspective are added in Scope 3. The specifically calculated sections of this paper are clearly included in the dotted rectangle in Figure 1. The dotted and shadow

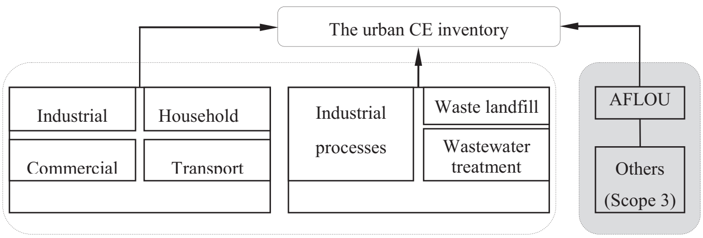

Figure 1. Accounting sectors (included in dotted rectangle) of Nanchang's CEs based on the GPC framework

rectangle represents the omitted sections, which contain the CEs of AFOLU types and other Scope 3 CEs. AFOLU emissions were not considered because they are highly uncertain and typically contribute a small amount to total city CEs. Emissions from Scope 3 were omitted because it was not possible to obtain sufficient original data, such as Nanchang's energy IO table. It can be seen that seven sectors are included in the dotted rectangle: industrial energy consumption, household energy consumption, commercial energy consumption, transportation, industrial processes, waste landfill and wastewater treatment. The first four sectors arise directly from energy use, while the last three sectors are process-related. CO_2e includes CO_2, CH_4, N_2O, CF_4 and C_2F_6. These can be transformed into CO_2e when multiplied by the global warming potential parameters, which were 1, 28, 265, 6,630 and 11,100, respectively, as recommended by the IPCC (2014).

2.2.1 Industrial energy consumption. The CEs of industrial energy consumption shows the emissions arising directly from all types of industrial energy combustion, for example, the paper-making industry. CEs can be calculated using the following equation:

$$C_I = \sum_i \left(\sum_j E_{ij} \cdot f_j \right) \tag{1}$$

where C_I denotes total CEs arising from industrial departments in unit tones, given by CO_2e ($t - CO_2e$), i denotes different subsectors of industrial departments (e.g. leather- and paper-making), j denotes the energy type (e.g. washed coal, liquefied gas and coke oven gas), E_{ij} denotes fuel combusted in i subsectors of industry and in the form of energy type j and f_j denotes the emission factor of different energy types. The energy-use data can be obtained from the Nanchang Statistical Yearbook, which is published yearly by the local government. Then, based on a suggestion from the IPCC, the emission factor can be obtained (listed in Table AI). By using the calorific value, the emission factor of heat can be calculated as $0.11t - CO_2e/GJ$. Finally, the emission factors of electricity for Nanchang are taken from the average values across China. These factors can be obtained directly from the International Energy Agency (IEA) statistics 2011-2015 (Table AII).

2.2.2 Household energy consumption. In daily life, coke oven, natural and liquefied natural gases, as well as electricity, are used in the household consumption sector. These fuels may arise from both primary and secondary energies. Their CEs can be calculated:

$$C_H = \sum_j (E_j \cdot f_j) \tag{2}$$

where C_H denotes the CEs of energy consumption in the household sector ($t - CO_2e$), E_j denotes the energy consumption of category j obtained from yearly statistical data and f_j denotes the same emissions factors as those stated in Section 2.2.1.

2.2.3 Commercial energy consumption. The energy consumption of the commercial sector is in the form of electricity. Its CEs are given by:

$$C_{CO} = E_e \cdot f_e \tag{3}$$

where C_{CO} denotes the electricity consumption CEs of the commercial sector ($t - CO_2e$); E_e denotes the quantity of electricity consumption (10^4 kWh), obtained directly from governmental statistical data; and f_e denotes the emission factor of electricity (Table AII).

2.3 Transportation

The transportation sector usually includes road, water and air transport. Road transport is the main contributor to CEs, while the other two account for no more than 30 per cent of total transport CEs (Bi *et al.*, 2011). Therefore, only the CEs of road transport were calculated based on the available data. For road transport, many kinds of vehicles exist, such as motorcycles, trucks (heavy, medium, light and micro), taxis, buses and passenger cars. These CEs are calculated as:

$$C_T = \sum_k \left(N_k \cdot VMT_k \cdot FE_k \cdot f_{g/d}\right) \times 10^{-6} \quad (4)$$

where C_T denotes the total CEs from energy consumption in the road transportation sector ($t - CO_2e$), k denotes the category of vehicle fleets, N_k denotes the number of vehicle fleet k, VMT_k denotes the annual average number of mile-meters traveled by vehicle fleet k (km/vehicle/year), FE_k denotes the fuel economy of vehicle fleet k (L/km) and $f_{g/d}$ denotes the emission factor of gasoline or diesel ($g\text{-}CO_2e/L$). The number of vehicles is obtained from the Nanchang Statistical Yearbook, and VMT information is obtained from a study by Wang *et al.* (2012). Finally, different CE categories of vehicle fleets were summed to obtain the total amount (C_T).

2.4 Waste

According to the IPCC (2006), CH_4 emitted from solid waste landfills accounts for 97 per cent of the total CEs in the waste treatment sector. Solid waste consists of both industrial and municipal solid waste. Thus, the method of the first-order decay model (FODM) recommended by the IPCC (2006), was also used to calculate solid waste CEs in this paper. Ideally, the FODM needs at least 20 years of data from the solid waste landfill. Fortunately, the related data for industrial and municipal solid waste can be obtained from statistical yearbooks, bulletins or local government documents. The related data are from 1994-2014, and the time series is 21 years. Thus, the FODM is suitable for this study.

$$C_{WATSE} = 28 \times \left[\sum_1 \left(CH_{41,t} - R_t\right)\right] \cdot \left(1 - OX_t\right) \quad (5)$$

where C_{WATSE} denotes the CEs of solid waste treatment ($t - CO_2e$), $CH_{41,t}$ denotes CH_4 production output of waste Type 1 during inventory year t (tones), R_t denotes CH_4 recovery for inventory year t (tones) and OX_t denotes the oxidation ratio for inventory year t (percentage).

Similarly, wastewater treatment CEs include both industrial and domestic wastewater. The related data can be obtained from local statistical materials. The recommended method is as follows:

$$C_{IWWATER} = 28 \times \sum_i \left[\left(TOW_i - S_i\right) \cdot f_i - R_i\right] \quad (6)$$

where $C_{IWWATER}$ denotes the CEs arising from industrial wastewater treatment ($t - CO_2e$), i denotes the industrial subsectors, as in Section 2.2.1, TOW_i denotes the total amount of biodegradable organic matter from i subsector industry in the inventory year (tones), S_i denotes the organic portion discharged by the sludge for the inventory year (tones),

$f_i$denotes the emission factor of industrial subsector i and R_i denotes the amount of CH_4 recovered during the inventory year (tones).

$$C_{DWWATER} = 28 \times \left\{ \left[\sum_{m,n} (U_m \cdot T_{m,n} \cdot f_n) \right] \cdot (TOW - S) - R \right\} \quad (7)$$

where $C_{DWWATER}$ denotes the CEs arising from domestic wastewater treatment ($t - CO_2e$); m denotes different income groups such as low, middle and high; n represents the different systems of disposing domestic wastewater for the inventory year; U_m denotes the population percentage of group m; $T_{m,n}$ denotes the degree of system n used by groupm; f_n denotes the emission factor of system n; TOW denotes the total amount of biodegradable organic matter from domestic wastewater (tones); S denotes total organic matter discharged by sludge for the inventory year (tones); and R denotes the total amount of CH_4 recovered during the inventory year (tones).

2.5 Industrial processes and product use

Industrial processes are the chemical or physical transformation path of materials during industrial production. This sector's CEs also have many categories. However, the basic data on these categories are scarce, so this sector's CE calculation focused on three major categories: mining, chemical and metal industries. The related production data can be obtained from yearly statistical materials and the emission factors from the IPCC report.

Mining industry: The mining industry is the largest CE source for the industrial processing sector. According to the IPCC, the mining industry includes cement, lime and glass production. These three are the major CE sources for the mining industry, and of these, cement production makes the greatest contribution. The corresponding CEs are:

$$C_{CE} = \left(M_{pr} \cdot p - M_{im} + M_{ex}\right) \cdot f_{cl} \quad (8)$$

where C_{CE} denotes the CEs during cement production ($t - CO_2e$), M_{pr} denotes the yield of cement production (tones), o denotes the ratio of cement clinker (default value is 0.65), M_{im} denotes the imported cement clinker (tones), M_{ex} denotes the exported clinker (tones) and f_{cl} denotes the emission factor of the clinker ($t - CO_2e/t -$ clinker, default value is 0.52).

Chemical industry: In the chemical industry subsector, many production processes exist, e.g. ammonia, nitric acid and carbon black production, all of which emit CEs, according to the IPCC. Based on the available data, only the CEs from the ammonia production process can be calculated:

$$C_{AM} = \left(M_{am} \cdot FD_{am} \cdot CC_{am} \cdot CO_{am} \times 44 \div 12 - R_{CO_2}\right) \times 10^{-3} \quad (9)$$

where C_{AM} denotes the CEs emitted from the ammonia production process ($t - CO_2e$), M_{am} denotes ammonia production (tones), FD_{am} denotes the fuel demand coefficient ($GJ/t -$ ammonia), CC_{am} denotes the carbon content coefficient (kg C/GJ), CO_{am} denotes the carbon oxidation rate (default factor is 100 per cent) and R_{CO_2} denotes CO_2e recovery in urea production (kg-CO_2e).

Metal industry: Many production processes that emit CEs also exist in the metal industry, e.g. those for steel, metallurgical coke, iron alloy, aluminum and magnesium. The emissions emitted from these production processes include not only CO_2 but also CH_4, CF_4 and C_2F_6.

They can be easily accounted for by multiplying the metal production number by the matching emission factors.

3. Results and discussion

3.1 Sectoral CO_2e emission

3.1.1 Industrial energy consumption CO_2e emission. More than 30 types of industrial subsectors exist, but data for these for 1994-1997 are not available. Thus, data for 1998-2014 are used in the related analysis. On the whole, CEs from all industrial subsectors in Nanchang increased from 8.17 Mt in 1998 to 9.55 Mt in 1999 (Figure 2). However, they decreased slightly to 8.31 Mt in 2000. For 2000-2007, they grew steadily to 20.51 Mt, with an annual rising rate of 13.78 per cent. Because of the impact of the global financial crisis in 2008, they decreased to 15.61 Mt in 2009. However, they recovered quickly to reach 21.44 Mt in 2010. Then, they continued to increase to 24.63 Mt in 2014, with an annual rate of increase of 3.54 per cent. The largest eight contributors were the industrial subsectors power, heat production and supply (PHPS), black metal smelting and rolling processing (BMSRP), chemical materials and product manufacturing (CMPM), paper-making and paper products (PMPP), transportation equipment manufacturing (TEM), non-metallic mineral products (NMMP), farm and sideline food processing (FSFP) and non-ferrous metal smelting and rolling processing (NFMSRP). For 1998-2014, these eight subsector CEs contributed 78.71-91.43 per cent to the total industrial CEs. The average contribution was 88.16 per cent. The first two subsectors (PHPS and BMSRP) contributed more than a half (>50 per cent), and the four subsectors PHPS, BMSRP, CMPM and PMPP contributed more than two-thirds (>72 per cent). The CEs from the eight industrial subsectors had different variation trends: NFMSRP and FSFP had the highest rates of annual increase of 16.82 and 13.55 per cent, respectively, while CMPM showed a rate of annual decrease of 9.67 per cent.

For total industrial CEs, the rate of increase after the 2008 crisis was lower than earlier ($3.54 < 13.78$ per cent). The main reasons for this drop were as follows. Since the twenty-first century, real estate and other infrastructure construction has expanded quickly in Nanchang. From 2000 to 2007, people ignored improved energy efficiency and focused only on gross domestic product (GDP) growth. Therefore, the economic structure became cumbersome and all eight industrial subsectors grew at the high rates of 194 (PHPS),

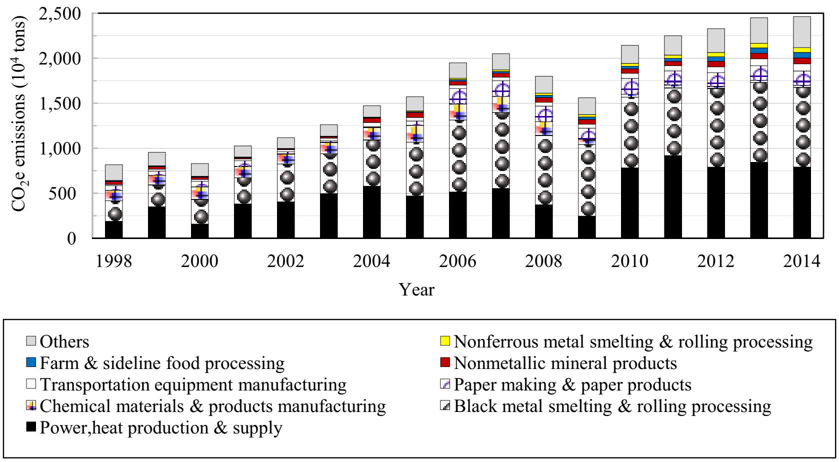

Figure 2. Accumulative results for the energy consumption CEs from all industrial subsectors

270 (BMSRP), 54 (CMPM), 235 (PMPP), 185 (TEM), 42 (NMMP), 122 (FSFP) and 306 per cent (NFMSRP). In 2008, the financial crisis occurred. Subsequently, preferences shifted to exploiting renewable energy, developing energy-saving technologies and removing inferior (energy-intensive or polluting) industries. For example, the inferior CMPM contribution to total industrial CEs decreased from 8.69 per cent in 2008 to 0.92 per cent in 2014. Simultaneously, people began to focus on the low-carbon economy and managed to improve energy efficiency. Therefore, the main subsectors showed only slight growth.

3.1.2 Household and commercial energy consumption CO_2e emissions. It can be easily seen that household CEs had an increasing trend on the whole, but they did show a slight decrease in 1999, 2008 and 2014 [Figure 3(a)]. Household CEs were 2.70 Mt in 2014, which is 24.97 times greater than the level in 1994. Similarly, commercial sector CEs had a total increase from 14.28 × 10^3 tones in 1994 to 0.38 Mt in 2014. However, they had a prominent decrease in 2009, 2012 and 2013 because of the 2008 financial crisis, industrial transformation and changes in energy prices in recent years [Figure 3(b)].

3.1.3 Transportation CO_2e emission. Five traffic types are considered: passenger vehicles, trucks, simple motors, motorcycles and steering wheel-type tractors (Figure 4). Total CEs in the transportation sector grew rapidly at an annual rate of 15.68 per cent in 1994-2004. Among the five traffic types, passenger vehicle CEs saw the highest growth rate, at 18.47 per cent, making them the largest contributor to the transportation sector. Truck CEs were the second largest contributor, and in 2014, passenger vehicles and trucks

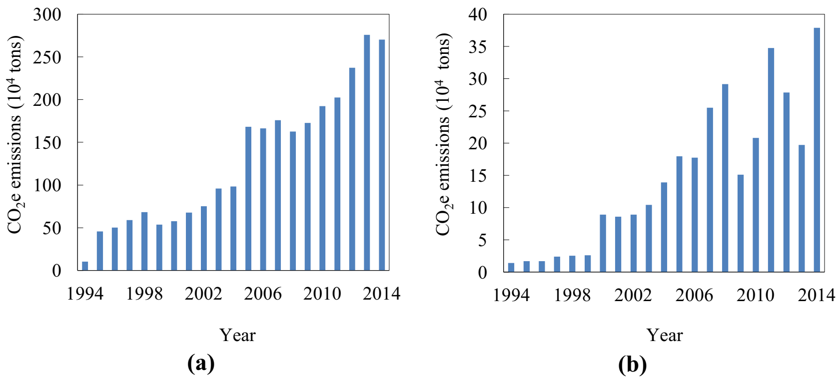

Figure 3.
CO_2e emissions from household (a) and commercial (b) energy consumption

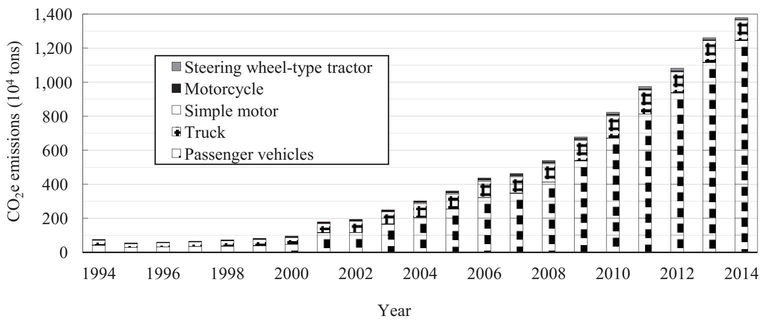

Figure 4.
Accumulated CEs of different traffic types

accounted for 90.34 and 8.74 per cent of total transport CEs, respectively. For 1994-2014, the sum of the CEs for these two types consistently had the majority share (>90.9 per cent, Figure 4), making the contributions of the other three types almost negligible.

The main three types of passenger vehicles were private cars, taxis and buses (Figure 5). Private car CEs had the largest increase, from 0.29 Mt in 1994 to 5.33 Mt in 2014. The increase was 5.04 Mt, more than 17 times that in 1994 and representing an annual increase of 15.65 per cent. In 1997, taxi CEs increased because of the substantial growth in taxi services, as seen in the official statistics [Figure 5(b)]. However, after 1997, the growth of private cars was much faster than that of taxis, so the share of taxis started to decline gradually until 2014. Overall, the average shares of private cars, taxis and buses were 87.36, 7.06 and 5.58 per cent, respectively.

3.1.4 Waste CO_2e emission. As shown in Figure 6, with the growth in the number of people, buildings and other man-made objects such as vehicles in Nanchang, the emissions of municipal solid waste landfill and domestic wastewater treatment increased steadily from 1994 to 2014. The average annual rate of increase for solid waste landfill was 15.95 per cent in 1998-2014 and that of domestic wastewater treatment was 1.44 per cent. However, the CEs of industrial solid waste landfill presented a slightly decreasing trend after 2008. This trend stemmed from improvements in production technologies and increases in the percentage of

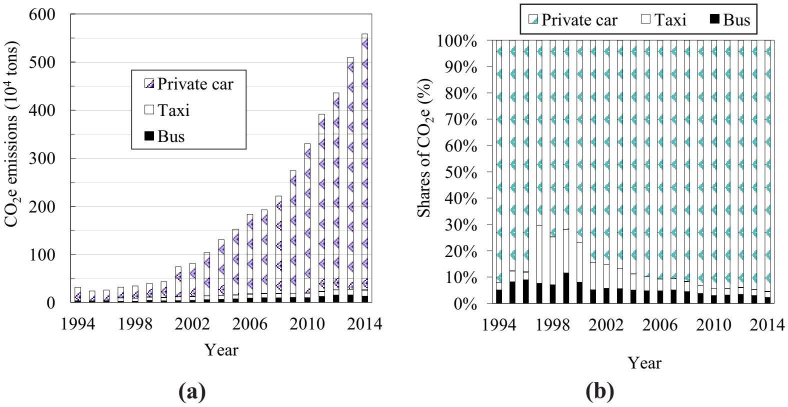

Figure 5.
CO_2e emissions for private cars, taxis and buses (a) and their respective shares (b)

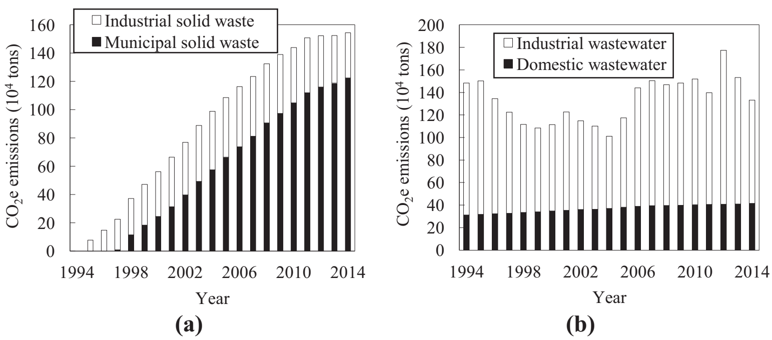

Figure 6.
CO_2e emissions from solid waste landfill (a) and wastewater treatment (b)

the comprehensive use of solid waste. In addition, the CEs of industrial wastewater treatment had no obvious change, perhaps because of the relatively stable patterns of social and economic development, lifestyles or local industrial policy.

3.1.5 Industrial process CO_2e emission. Obviously, CEs from the industrial process sector increased in 1994-2014, but they experienced a prominent decrease in 2008 (Figure 7). The change trend was similar to that for total industrial CEs or household CEs. This decrease also stemmed from the worldwide financial crisis in 2008. CEs were 10.62 Mt in 2014 and were 8.31 times greater than that in 1994 (1.14 Mt). The average annual rates of increase were 89.36 per cent prior to 2008 and 6.69 per cent thereafter. Steel, pig iron and cement had the biggest shares in this sector's CEs. The combined share of these three contributed more than two-thirds of the total industrial process CEs (>73.84 per cent), reaching a peak of 98.18 per cent in 2013. The share of synthetic ammonia was 26.07 per cent in 1994, but it decreased to 0 per cent in 2011-2014 because of an inferior industrial removal plan. The share of aluminum was always below 2.22 per cent in 1994-2014.

3.2 CO_2e emissions for different types of energy

Figure 8 shows the CEs resulting from the use of different types of energy such as crude coal, washed coal, other washed coal, coke, coke oven gas, natural gas, diesel and electricity. Emissions from other fuel types were minimal and are thus omitted. The CEs of crude coal were 5.93 Mt in 1994. These increased to their peak, 8.55 Mt, in 2011, and in 2014, coal's CEs had dropped to 7.00 Mt. Over the period of 1994-2014, crude coal CEs saw several declines. In particular, after 2008, they decreased to their lowest, 2.20 Mt, in 2009. Overall, crude coal increased at a much lower rate than other forms of energy such as coke and electricity. Therefore, the share of crude coal CEs had a reverse decreasing trend, dropping from 70.58 per cent in 1994 to 28.57 per cent in 2014. Similarly, the share of diesel CEs decreased from 0.57 to 0.43 per cent, but its rate of decline was slower than that of crude coal. The emission numbers and shares of other energy types increased during the study period. For example, in 2014, the shares of electricity, coke and washed coal increased to 38.49, 17.04 and 12.21 per cent, respectively. In total, the shares of crude coal, washed coal, other washed coal and electricity can be added to find that consistently, over 74.41 per cent of Nanchang's CEs were related to coal; because, in China, most electricity was generated by coal burning in 1994-2014.

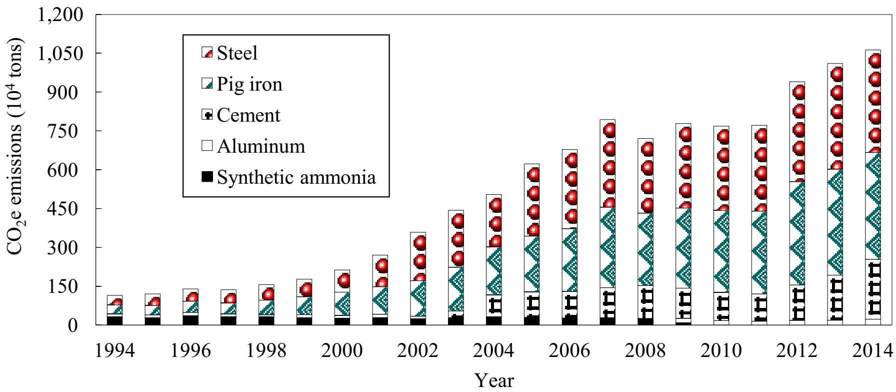

Figure 7.
CO_2e emissions from the industrial process sector

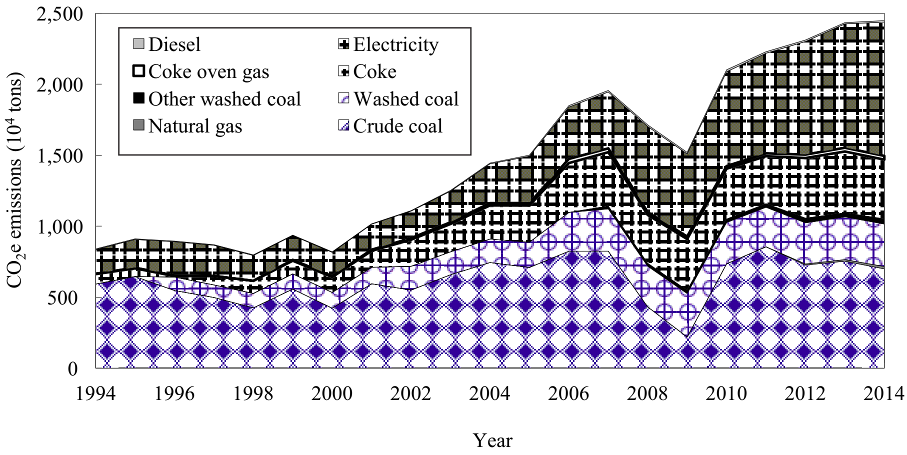

Figure 8.
CO_2e emissions from different fuel types

3.3 Total CO_2e emissions of Nanchang

Figure 9 shows total CEs and subsector CEs for Nanchang. It can be seen that the total CEs increased steadily, with a slight decrease only in 2008-2009 (Figure 9). Total CEs were 12.49 Mt in 1994, and they grew rapidly to 37.83 Mt in 2007. However, emissions then decreased to 34.62 Mt in 2008 and to 34.20 Mt in 2009. After 2009, they steadily increased again to 55.00 Mt in 2014. The average annual rate of increase was 8.89 per cent for 1994-2007 and 9.51 per cent for 2009-2014. Industrial energy consumption CEs (1) accounted for 44.71-72.06 per cent of total CEs. Transportation energy consumption CEs (2), household energy consumption CEs (3), commercial energy consumption CEs (4), industrial process CEs (5), solid waste landfill CEs (6) and wastewater treatment CEs (7) accounted for 4.10-25.07, 0.83-5.67, 0.11-0.83, 9.07-22.28, 0.00-4.09 and 2.42-11.87 per cent, respectively. The shares of (1) and (7) declined because the shares of the other five sectors increased steadily.

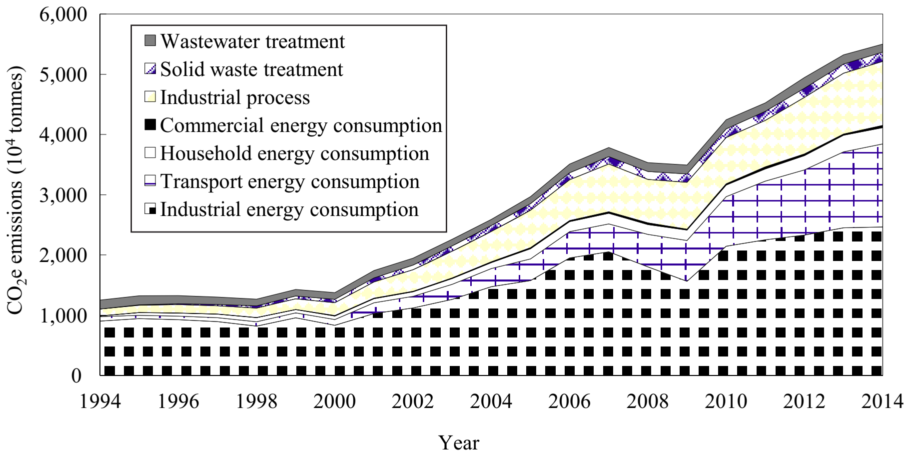

Figure 9.
Total CEs and different subsector CEs in Nanchang city

It can be easily seen that industrial energy consumption CEs (1) were the largest contributor to total CEs. Further, (1) emissions continued to have steady growth (Figures 2 and 9), although their share was declining. Transportation energy consumption CEs (2) were the second greatest contributor, and industrial process CEs were the third. These three contributors accounted for more than 85.14 per cent of the city's total CEs. Therefore, it can be concluded that much more attention should be paid to the CEs of these three subsectors when studying the low-carbon future or designing the sustainable development of Nanchang.

3.4 CO_2e emission intensities

Table II shows the total CEs of Nanchang, CEs per unit area, population, CEs per capita, GDP, CEs per GDP and the shares of primary, secondary and tertiary industry in 1994-2014. The table clearly shows that the CE intensities (CE per GDP) decreased from 32.48 in 1994 to 6.81t-CO_2e/10^4\$ in 2014, representing a 79.03 per cent decline. This decline may have been driven by improvements in industrial technology. However, per capita CEs increased from 3.21 t to 10.62 t during the study period. Total CEs decreased from 2008 to 2009 because of the financial crisis, but they grew almost 2.5 times more than earlier. This result might stem from improvements in living standards and the prosperity of the real estate construction industry in recent years. Similarly, from 1994 to 2014, the CEs per unit area increased from 1.69 to 7.43 × 10^3 t-CO_2e/km^2, an increase of 3.4 times. In addition, GDP, similar to total CEs, increased steadily during the study period. The only difference from CEs was that GDP continued to increase in 2008. All in all, the GDP was positively related to total CEs.

Table II.
Total CEs, CEs per unit area, population, CEs per capita, GDP, CEs per GDP and the shares of primary, secondary and tertiary industries in Nanchang city

Year	CE	CEs per unit area	Population	CEs per capita	GDP	CEs per GDP	Primary industry	Secondary industry	Tertiary industry
1994	1,249	1.69	389	3.21	38.47	32.48	18.42	44.08	37.51
1995	1,321	1.78	395	3.34	50.04	26.40	16.23	45.44	38.32
1996	1,324	1.79	402	3.30	64.64	20.48	15.99	44.90	39.11
1997	1,299	1.76	408	3.19	81.68	15.91	14.31	45.38	40.31
1998	1,265	1.71	416	3.04	89.46	14.14	11.02	46.43	42.55
1999	1,426	1.93	424	3.36	94.83	15.04	11.80	45.79	42.40
2000	1,373	1.85	433	3.17	105.58	13.00	10.90	45.76	43.34
2001	1,740	2.35	440	3.95	122.67	14.19	10.20	45.88	43.92
2002	1,946	2.63	449	4.34	139.25	13.97	9.49	47.03	43.47
2003	2,260	3.05	451	5.01	150.68	15.00	8.57	48.42	43.02
2004	2,590	3.50	461	5.62	170.04	15.23	8.08	50.45	41.47
2005	2,968	4.01	475	6.25	199.02	14.91	7.20	52.81	39.99
2006	3,508	4.74	484	7.25	235.99	14.86	6.53	54.27	39.21
2007	3,783	5.11	491	7.70	274.03	13.81	6.24	54.27	39.49
2008	3,532	4.77	495	7.14	331.29	10.66	6.11	55.39	38.50
2009	3,492	4.72	497	7.02	387.98	9.00	6.09	55.32	38.59
2010	4,244	5.73	502	8.45	459.86	9.23	5.46	56.73	37.81
2011	4,524	6.11	505	8.96	526.90	8.59	5.02	58.73	36.25
2012	4,945	6.68	508	9.74	629.09	7.86	4.91	56.45	38.65
2013	5,322	7.19	510	10.43	727.41	7.32	4.60	54.86	40.54
2014	5,500	7.43	518	10.62	807.88	6.81	4.44	54.99	40.57

Notes: GDP was converted to purchasing power parity based on constant 2011 international values. The units for Columns 2-10 are 10^4t-CO_2e, 10^3t-CO_2e/km^2, 10^4person, t-CO_2e/person, 10^8\$, t-CO_2e/10^4\$, %, % and %, respectively

The economic structure of Nanchang experienced an obvious change from 1994 to 2014: the share of primary industry decreased from 18.42 to 4.44 per cent. In contrast, the share of secondary industry increased from 44.08 to 54.99 per cent. However, tertiary industry only saw a slight rise of no more than 3 per cent (Table II). These trends indicate that economic development in Nanchang relied increasingly on secondary industry, which might explain why the worldwide economic recession that broke out in 2008 did not impact Nanchang's GDP growth but did cause total CEs to decrease.

3.5 Comparison with China and the world

It should be noted that total CEs for Nanchang include Scope 2 electricity CEs, which is electricity used within the city's geographical boundary. The related CEs could be called electricity consumption-related CEs or consumption-based CEs (ECCEs). For Nanchang City, in this paper, three types of ECCEs were identified based on the available data: industrial, household and commercial. These three types were included in industrial energy consumption CEs, household energy consumption CEs and commercial energy consumption CEs, respectively. In contrast, many cities in China have power plants located within their geographical boundaries to generate and sell electricity to the national power grids (Bi *et al.*, 2011). The emissions from these power stations (production-based view) were mixed in with the industrial energy consumption CEs. The mixed sub-industrial emissions are called PHPS. In the PHPS's CE, the share of heat production and supply was very small, and it was not possible to differentiate it from PHPS overall because of the hybrid nature of the statistical data. In other words, the electricity production-related CE or production-based CE (EPCE) was included in PHPS's CE and represent the major portion. However, it was not possible to acquire definitive data for the EPCE. As can be seen in Figure 10, the PHPS's CE column is empty for 1994-1997 because of the lack of corresponding PHPS's data, and the total ECCEs (commercial, household and industrial) have a steadily increasing trend for 1994-2014. Nevertheless, the EPCE (included in PHPS's CE) had a clear recession in 2008-2009 because of the economic crisis. In this paper, CE accounting included both electricity use and its production, which might cause double counting and some deviations. Therefore, in the later comparison of Nanchang, China, with the world, electricity CEs were excluded.

As discussed above, Nanchang's CEs arising from coal, oil and gas consumption were compared with those of both China and the world. The corresponding results are shown in Table III. It can be easily seen that the CEs per GDP of Nanchang are consistently smaller than those for China. However, they are always larger than worldwide CEs. Thus, it is clearly increasingly urgent and necessary to save energy and improve energy efficiency in

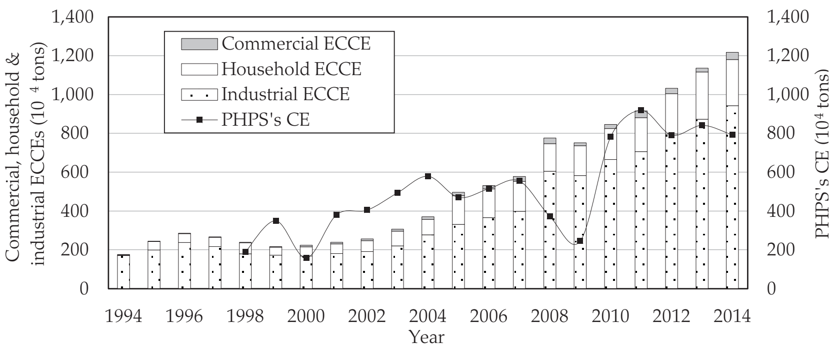

Figure 10.
ECCEs comprising commercial, household and industrial CEs; EPCEs are included in the PHPS's CE

Year	NC	CE (Mt) CN	WD	CEs per capita (t-CO_2e/person) NC	CN	WD	CEs per GDP (t-CO_2e/$10^4$$) NC	CN	WD	CEs per unit area (10^3t-CO_2e/km^2) NC	CN	WD
1994	7.81	3,029	23,101	2.01	2.53	4.11	20.32	29.55	4.58	1.06	0.31	0.16
1995	8.00	3,228	23,564	2.02	2.67	4.13	15.98	25.90	4.52	1.08	0.34	0.16
1996	7.51	3,323	24,185	1.87	2.72	4.18	11.62	22.31	4.47	1.01	0.34	0.16
1997	7.52	3,314	24,423	1.84	2.68	4.16	9.21	19.16	4.34	1.02	0.34	0.16
1998	7.22	3,312	24,510	1.74	2.66	4.12	8.07	17.42	4.25	0.98	0.34	0.16
1999	8.78	3,423	24,853	2.07	2.72	4.12	9.26	16.96	4.16	1.19	0.36	0.17
2000	7.69	3,514	25,501	1.78	2.77	4.17	7.29	15.51	4.08	1.04	0.36	0.17
2001	10.42	3,674	25,825	2.37	2.88	4.17	8.50	14.25	4.03	1.41	0.38	0.17
2002	11.41	4,025	26,436	2.54	3.13	4.21	8.19	14.38	4.02	1.54	0.42	0.18
2003	13.12	4,723	27,718	2.91	3.65	4.36	8.70	16.19	4.06	1.77	0.49	0.19
2004	15.16	5,521	29,143	3.29	4.25	4.53	8.92	17.20	4.05	2.05	0.57	0.20
2005	15.98	6,326	30,279	3.36	4.84	4.65	8.03	17.23	4.02	2.16	0.66	0.20
2006	19.90	6,926	31,187	4.11	5.27	4.73	8.43	15.96	3.93	2.69	0.72	0.21
2007	20.93	7,518	32,307	4.26	5.69	4.84	7.64	14.23	3.86	2.83	0.78	0.22
2008	17.15	7,663	32,597	3.47	5.77	4.82	5.18	12.13	3.78	2.32	0.80	0.22
2009	16.45	8,037	32,004	3.31	6.02	4.68	4.24	11.01	3.72	2.22	0.83	0.21
2010	23.05	8,472	33,471	4.59	6.32	4.83	5.01	9.94	3.70	3.11	0.88	0.22
2011	25.39	9,206	34,413	5.03	6.83	4.91	4.82	9.70	3.66	3.43	0.96	0.23
2012	26.39	9,415	34,819	5.20	6.95	4.91	4.19	8.41	3.58	3.56	0.98	0.23
2013	28.65	9,674	35,312	5.62	7.11	4.92	3.94	7.58	3.52	3.87	1.00	0.24
2014	29.27	9,761	35,499	5.65	7.14	4.89	3.62	6.97	3.42	3.95	1.01	0.24

Note: The CEs for China and the world were taken from the BP Statistical Review of World Energy, BP Global 2015

Table III. Differences in four emission indicators for Nanchang (NC), China (CN) and the world (WD)

Nanchang from a global perspective. In particular, a similar result can be obtained from looking at CEs per unit area: Table III shows that CEs per unit area for Nanchang were consistently greater than those for both China and the world.

In contrast, the per capita CEs of Nanchang were only 2.01 t in 1994, which is below the level of contemporaneous China (2.53 t) and the world (4.11 t). In 2011, the per capita CEs of Nanchang (5.03 t) first surpassed global CEs (4.91 t) but were still below those of China (6.83 t, Table III). These accumulative CEs per capita for Nanchang were consistently below those of China and the world for 1994-2014 (Figure 11). These results mainly stem from the

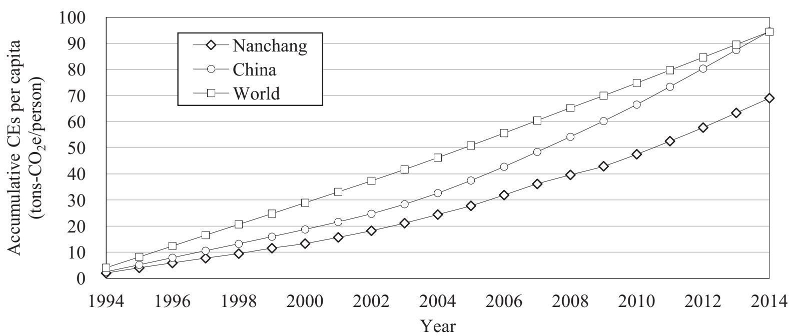

Figure 11. Accumulative CEs per capita for Nanchang, China, and the world

underdeveloped nature of Nanchang compared with cities in developed countries or with developed cities in China, such as Beijing and Shanghai.

3.6 Uncertainties

Some common sources of errors or uncertainties exist when calculating the CEs of any place such as a city, town or country. For example, rounding errors may exist in calculation processes, or real-world emission variability may confuse emission factors. In this article, the main uncertainties in the CE calculation of Nanchang may be rooted in the following issues. First, the emission factors of different types of energy/products may have some inherent uncertainties. For example, the related data for China are directly adopted from the IEA statistics and the IPCC: the emission factors for electricity are directly from the IEA, and the other factors are mainly from the IPCC. Especially, in industrial processes and solid waste landfill and wastewater treatment, default emission factors are often used. Second, the calculation model may have some unpredicted and systematic errors, such as the IPCC-recommended FODM. This method is used to calculate solid waste CEs from a global point of view. However, the decay speed and mode for solid waste may vary as the influencing factors change, such as time, place and climate. In other words, the model may differ from the actual situation in Nanchang. In addition, the lack of some data sources could mean that the calculated result for Nanchang is smaller than the actual amount. For example, the CEs of only five industrial processes, steel, pig iron, cement, aluminum and synthetic ammonia production, are calculated. The result may be lower than the actual emissions from all industrial processes in Nanchang. Similarly, the CEs from electricity consumption are only calculated for the commercial energy consumption sector, which may also make the results lower than real values.

4. Conclusions

Currently, CE accounting for cities is needed to combat climate change. Scholars have suggested several urban CE accounting frameworks (bottom-up, top-down and hybrid methods) through case studies addressing typical developed global cities such as London, Los Angeles, Xiamen and Nanjing. However, these cases and methods often cannot be applied directly to underdeveloped cities, e.g. cities in the Poyang Lake region of Jiangxi Province in Central China, because of disparities in statistical indexes or missing data. Therefore, taking Nanchang (an underdeveloped city in the Poyang Lake region) as an example, the authors complete an urban CE calculation based on the available data and the recently developed GPC method, a framework that is considered to provide globally comparable results. The specific sectors calculated are industrial energy consumption, transportation, household energy consumption, commercial energy consumption, industrial processes and waste landfill and wastewater treatment.

The results show that Nanchang's CEs grew rapidly from 12.49 Mt in 1994 to 55.00 Mt in 2014, with a recession in 2008 because of the global financial crisis. The three largest contributors were industrial energy consumption, transportation energy consumption and industrial processes, with each contributing 44.71-72.06, 4.10-25.07 and 9.07-22.28 per cent, respectively, to total CEs. The CE intensity (CEs per GDP) has decreased from 32.48 to 6.81 t-$CO_2e/10^4$\$ from 1994 to 2014 because of improvements in industrial technology. Per capita CEs have increased from 3.21 to 10.62 t because of recent improvements in living standards and the thriving real estate construction sector. The CE share of crude coal decreased from 70.58 to 28.57 per cent from 1994 to 2014, while the CE shares of electricity, washed coal and other washed coal increased to 38.49, 12.21 and 1.52 per cent, respectively, in 2014. Because most electricity originated from coal burning in China, when the shares of these four are added, it can be seen that almost always, more than 74.41 per cent of Nanchang's CEs in 1994-2014 were related to coal. According to the GPC framework, the total CEs contained electricity CEs from Scope 2. Therefore, the CEs from both electricity use and its production were accounted for. However, these results might include double counting and cause some deviations because of the hybridity of the data for Nanchang. Thus, only the CEs from coal, oil and gas (excluding electricity) were considered when comparing the results for Nanchang with those for China and the world. The results showed that the accumulative CEs per capita for Nanchang were consistently lower than those for China and the world for 1994-2014, because Nanchang was still underdeveloped. However, the CEs per GDP for Nanchang were always greater than worldwide CEs. In addition, the CEs per unit area for Nanchang were always greater than those both for China and worldwide. Thus, from the global view, there is an urgent need to both save energy and improve energy efficiency in Nanchang.

Based on these results, the following implications for strategies and policies to combat climate change can be inferred.

First, to achieve a low-carbon future, or sustainable development, Nanchang should focus attention on developing new industries using low-carbon energy sources such as solar instead of traditional industries using high-carbon fuels such as petrol or coal. At the same time, in specific industrial subsectors, various carbon mitigation countermeasures should be adopted based on their individual context. For example, a cost-benefit comparison of CE reduction could be conducted to determine development priorities in the industrial subsectors of PMPP, TEM and FSFP, among others. Then, low-carbon related knowledge, policy, education and lifestyles could be promoted.

Second, from the perspective of transportation energy consumption, city residents, especially private car owners, should be encouraged to drive less and to walk or choose public transportation methods such as the bus or subway to the greatest extent possible. The development of some new low-carbon traffic tools that use new energy sources instead of traditional high-carbon fuels should be pursued. Even so, transportation sector CEs and their overall share will likely increase rapidly given the transformation or renovation of the transportation infrastructure, the rise of wealth and traffic demand (Wang *et al.*, 2012). Therefore, beyond new fuel sources and guides to low-carbon lifestyles as mentioned above, other influences must be comprehensively considered when developing low-carbon transportation policies in Nanchang.

Third, considering only the CEs from coal, oil and gas, the accumulative CEs per capita for Nanchang were consistently lower than those for China or worldwide during 1994-2014. However, it still cannot be said that promulgating energy-saving or low-carbon development strategies in Nanchang is unnecessary because Nanchang itself is still underdeveloped. With accelerating industrialization, excessive CEs and related problems will gradually emerge in the city. Thus, strategies and management policies should be vigorously encouraged to combat climate change in Nanchang.

Fourth, this is the first study of the CEs for Nanchang City and thus clearly an innovation; further, the results show that the GPC framework offers strong comparability and generalizability. Thus, this method deserves active promotion and application to other similar underdeveloped cities, especially those cities in the Poyang Lake Region of Jiangxi Province in Central China. Moreover, the conclusions and suggestions of this study are representative and significant for underdeveloped cities worldwide. For instance, more than 74.41 per cent of Nanchang's CEs were linked to coal during 1994-2014. A similar problem may exist in many other underdeveloped cities around the world. Accounting using the GPC framework can provide more scientific data to justify related carbon mitigation countermeasures and thus increase public understanding and trust in these measures.

Finally, as mentioned above, the lack of some data sources may mean that Nanchang's calculated CE is smaller than its reality. Thus, it can be inferred that local and central governments should strive to improve the collection and sorting of the relevant index databases considering the data set requirements of the GPC framework. Furthermore, the emission factors for some energy types in Nanchang cannot be directly obtained from the related public literature. Therefore, the government should also encourage scientists to actively engage in the related research work, and periodically, it could supply sufficient funds to support related scientific research work, such as monitoring and verifying the related emission factors.

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Appendix

Table AI.
The CE factors of different types of energy

Energy type	Carbon content (kg/GJ)[a]	Carbon oxidation (%)[a]	Emission rate (kg-CO_2e/TJ)[a]	Net calorific value (TJ/Gg)[a]	Emission factor (t-CO_2e/t)
Crude coal	25.8	100	94,600	20.9	1.977
Washed coal	25.8	100	94,600	26.3	2.488
Other washed coal	25.8	100	94,600	8.4	0.795
Briquette	26.6	100	97,533	17.6	1.717
Coke	29.2	100	107,067	28.2	3.019
Coke oven gas	12.1	100	44,367	16,726[b]	7.421[c]
Natural gas	15.3	100	56,100	38,931[b]	21.840[c]
Liquefied natural gas	17.5	100	64,167	44.2	2.836
Crude oil	20.0	100	73,333	42.3	3.102
Gasoline	20.2	100	74,067	43	3.185
Kerosene	19.5	100	71,500	44.1	3.153
Diesel	20.2	100	74,067	43	3.185
Fuel oil	21.1	100	77,367	40.4	3.126
Liquefied petroleum gas	17.2	100	63,067	47.3	2.983
Other petroleum products	20.0	100	73,333	40.2	2.948

Notes: [a]The value is the IPCC-recommended value; [b]the unit is kJ/m^3; [c] the unit is t-CO_2e/10^4 m^3

Table AII.
Emission factor of electricity (t-CO_2e/10^4 kwh)

Year	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Emission factor	9.012	9.030	8.994	8.958	8.922	8.886	8.850	8.835	8.820	8.805	8.790
Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	–
Emission factor	8.670	8.620	8.220	7.970	7.900	7.580	7.640	7.700	7.760	7.820	–

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