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Exploring an integrated urban carbon dioxide (CO_2) emission model and mitigation plan for new cities

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Abstract

Mitigating carbon emission efforts in urban planning and design phase have become increasingly popular due to climate change. However, it is difficult to verify whether the carbon mitigation target could be achieved for a new city in the absence of quantitative analysis methods. About 100 new cities have emerged every year in the past decades, yet few of them employed low carbon strategies within proper prediction methods. In response, this paper offers an integrated analysis method of assessment and mitigation for urban carbon dioxide (CO_2) of new cities. Building sector, transportation sector, and green land sector are considered as urban CO_2 sources and sink. Life cycle analysis was employed in building sector to estimate its emissions. Based on the current and predicted emission data, a mitigation goal was then set and allocated efficiently through different sectors. To elaborate on this process, a case study of Shanghai Lingang New City was presented. The urban low carbon roadmap was planned and a variety of recommendations concerning policy were offered to assist the local government and policy makers in order to achieve the low carbon development goal as well.

Keywords

Urban carbon emission, life cycle analysis (LCA), carbon dioxide (CO_2) mitigation, new cities, energy efficiency

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Introduction

The world's cities are at the forefront of our battle against climate change simply because people, infrastructures, and commercial activities are most concentrated in cities, resulting in high energy consumption and high greenhouse gas (GHG) emissions. Occupying just two percent of land, they are responsible for up to 70 percent of GHG emissions (Habitat, 2011). In recent years, China's CO_2 emissions have increased significantly as a result of rapid economic development, doubling between 2000 and 2007 (He, 2007). Now China has become the largest carbon emission country in the world (ref). Moreover, the 35 largest cities in China, containing 18% of the population, contribute 40% of China's energy uses and CO_2 emissions (Dhakal, 2009). Unlike developed countries, most cities in China are still under industrialization and in the coming two decades China will be the main driver of a 40% increase in global energy consumption (Blok, 2012). This may provide an opportunity for China to avoid costly measures to cut emissions down the road if they start now to set carbon mitigation goals in the planning and design phases.

In the planning and design practices, many cities are engaging in the climate change efforts with ambitious goals and practical plans. For example, more than 400 towns and cities in the EU and the US have implemented the *Climate Change Action Plan*, including London, Grand Paris, Berlin, Portland, Los Angeles, Miami, Chicago, etc. According to the *European Covenant of Mayors*, covenant signatories aimed to meet and exceed the European Union 20% CO_2 reduction objective by 2020. London was set on a strong course to cut its carbon output by 60% by 2025 (City of London, 2010); Berlin's mitigation target is 40% lower by 2020 (City of Berlin, 2011), and Grand Paris, 20% (Grand Paris Seine Ouest, 2011); Portland was planning to cut GHG emissions by 40% by 2030, and 80% by 2050 (City of Portland and Multnomah County, 2009). In Los Angeles, the goal was to cut carbon emissions by 35% by 2030 compared to the 1990 levels (City of Los Angeles, 2007). All these cities have made building and transportation the most important sectors for CO_2 mitigation.

However, these low-carbon plans in developed countries may not directly be applied to the low carbon planning for new cities in developing countries. For these cities, an important theme for the past two decades or so is urbanization, which has had profound impacts on the outlook of today's world (Angel et al., 2011). This trend is particularly true for populous developing countries such as China and India. In the past 30 years, an estimated 500 million Chinese have become urbanized and 400 million more will do so by 2025, when India will see an increase of 215 million in urban population too. Together by that time these two countries will have 1.4 billion people living in cities (United Nations, 2010). Such rapid and massive social changes are creating huge challenges for infrastructure development, energy production, and certainly our efforts in fighting climate change (Salon et al., 2010). In fact most of the existing cities in these countries are already facing a wide variety of environmental and developmental problems (Dodman et al., 2012). Thus the research question is: how do the Chinese new cities achieve CO_2 reduction goals based on robust urban CO_2 emission inventories?

In studies on urban CO_2 emission estimates, most discussions in the past decades were focusing transport systems, buildings or green systems separately (Williams, 2013). There were literatures also studying transport emissions derived from land use or urban form shifts (Banister et al., 1997; Lee and Lee, 2014; Ma, 2014; Parshall et al., 2010; Ye et al., 2015). Integrated CO_2 modeling and mitigating planning in urban systems has been less well documented (Williams, 2013). For the urban CO_2 emission studies, there were studies focusing on household emissions (Goodall, 2007). This method was helpful for individual

CO_2 emissions mitigation strategy, but not appropriate for guiding city governmental low carbon planning. Brown et al. developed an integrated approach, one that coordinates across architectural design, building operation, smart growth concepts, and polices, is developed qualitatively to address GHG emissions in US (Brown and Southworth, 2008; Brown et al., 2005). This integrated approach was a comprehensive assessment of carbon emission at city scales, yet lack of systematic calculations. Emerging studies used systematic models to estimate urban-level CO_2 emissions, which were most did in US cities and European cities (Blok, 2012; Feliciano and Prosperi, 2011; Glaeser and Kahn, 2008). For example, Glaeser and Kahn (2008) developed a method of calculating urban-level CO_2 emissions, and applied this method to 10 US cities. They divided the emission sources into driving, public transportation, heating, and electricity usage. This inventory method was applicable for local government making mitigation and adaptation plans. In developing countries, Lo et al. tried to find relationships between urban form and energy consumption in four cities in Southern China, and his conclusion is consistent with most studies of land use and urban energy (Keistread and Shah, 2011; Lo et al., 2007; Mindali et al., 2004; Newman and Kenworthy, 1989). However, he did not explain the reason of the relationship. Fong et al. (2009) developed a dynamic model, ''FML'', to explain CO_2 emission structure for a developing Malaysian city. Several policies based on it were then recommended. He concluded that the residential sector did not contribute to CO_2 emissions according to his model, which was inconsistent in other studies. Feng et al. (2013) developed a system dynamics model for urban energy consumption and CO_2 emissions for Beijing, China. This system model supplied an acceptable estimate of urban CO_2 emission methods, but still a rough approach for it lacked life cycle analysis (LCA) analysis.

In conclusion, there were lack of relevant studies considering context and data of new cities in developing countries. Even for the general studies in developed cities, there was lack of Life Cycle Assessment (LCA) of urban CO_2 emissions. LCA is a process whereby the material and energy flows of a system are quantified and evaluated over the whole life span of the given system (Kneifel, 2010; Pérez-Lombard et al., 2008; Scheuer et al., 2003), representing a comprehensive approach to examining the CO_2 emissions of an entire building. In response, this paper established a bottom-up carbon emission assessment model in accordance with actual conditions in China, which could quickly calculate carbon emission of a city under certain circumstances, thus making a low-carbon plan possible. The research scope consisted of building carbon emission analysis using LCA method, traffic emission analysis, and green space carbon sink analysis; a low-carbon plan could then be developed based on this system. In this paper we used the central district of Lingang New City, Shanghai (henceforward called ''Lingang'') as a case study to provide a framework and method for low carbon urban planning in China. Lingang is currently under rapid construction and development. Infrastructure and real estate projects are to be finished by 2020; the population will continue to grow until the year 2025 according to Lingang's comprehensive plan. Our objective is to analyze this development process and set achievable carbon reduction goals for the city. LCA method was used for CO_2 emissions assessment and predictions, and then reduction goals could be set and allocated effectively among different sectors. Based on above, a low-carbon roadmap would be developed for the urban planners as the final product.

Methods

The framework of urban carbon emission model contained three components: the building sector, the transportation sector, and urban green systems. After estimating growth rate and trends of each component, mitigation goals were set, which would be further justified by three factors: economics, low-carbon technologies, and demographic trend. Then the total emission reduction amount was decomposed to sub sectors to help achieve the mitigation goals. This model was applied to a new city in China—Lingang as a case study. The framework of this study is shown in Figure 1.

Calculation of urban CO_2 emissions

Urban CO_2 emissions in cities mainly come from buildings and transportation, while urban green systems can absorb a certain amount of CO_2. Urbantotal urban CO_2 emissions are calculated as

$$C^E = B^{CE} + T^{CE} - G^{CF} \tag{1}$$

where C^E is total CO_2 emissions; B^{CE}, building carbon emissions; T^{CE}, transportation carbon emissions; G^{CF}, urban green carbon fixation, which are the amounts of CO_2 absorption by urban green systems.

This paper calculated CO_2 emissions of different sectors based on methodologies provided by the Intergovernmental Panel on Climate Change guidelines. Simple estimation procedures rely on activity data and emissions factors. The equation is

$$C^E = C \times I \tag{2}$$

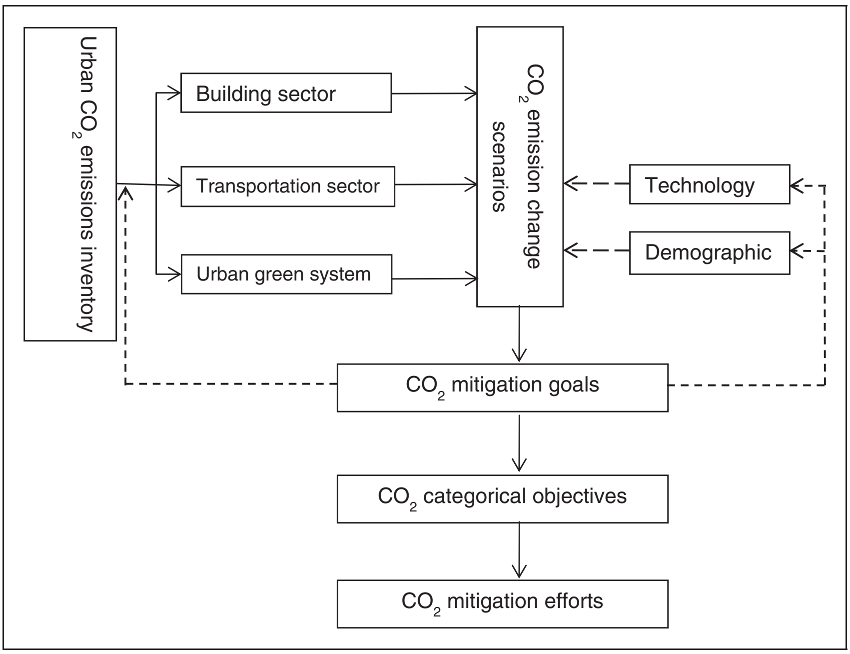

Figure 1. Research framework of urban carbon planning model for new cities.

where C is activity data and I is emissions factor. Activity data and emissions factors vary a lot between emissions sections and are also dependent on specific statistical methods used. In this research they were generated empirically through local investigations, and/or from published data in the literature. Detailed framework and methods are given below.

Calculation of building CO_2 emissions

Building CO_2 emissions, B^{CE}s, were calculated by LCA. Typically, a building's life cycle could be divided into four stages: (I) Production and transportation of building materials; (II) Construction; (III) Operation; (IV) Demolition and recycle of usable materials. CO_2 emissions from each stage have different features and need to be calculated separately. In this paper we used two different types of calculation: B^{CE} was the realistic emissions, and $\overline{B^{CE}}$ was the average emissions (i.e. realistic emissions of stages I, II, and IV, often counted as one-time emissions, were averaged over the life span of the buildings, providing a more meaningful estimate of B^{CE}). The B^{CE} of the nth year in a building's life span N ($N = 50$ was used for both public and residential buildings) is given by equations (3) and (4)

$$B_n^{CE} = \sum B_{n,i}^{CE} \tag{3}$$

$$\overline{B_n^{CE}} = \sum \overline{B_{n,i}^{CE}} \tag{4}$$

where $i = 1$ to 4 represents the four stages of a building as discussed above. Detailed calculations of B^{CE} at each stage in the nth year are given below.

CO_2 emissions in the period of materials production and transportation (${B^{CE}}_{n1}$) are from raw materials production and carriage, which include steel, cement, sand, glass, wholesome pottery, and other building materials. In this period, data to be collected include the quantity of each material consumed and energy consumption in the transportation

$$B_{n,1}^{CE} = \sum_{j=0} \sum_{k=0} E_k \times M_{k,j} \times S_{n,j} \tag{5}$$

$$\overline{B_{n,1}^{CE}} = \sum_{j=0} \sum_{k=0} \frac{E_k \times M_{k,j} \times S_{n,j}}{N} \tag{6}$$

where $B_{n,1}^{CE}$ is the realistic CO_2 emissions; $\overline{B_{n,1}^{CE}}$, the average emission; E_k is emissions in the production of unit quantity of material k ($k = 0$: Steel; 1: Cement; 2: Concrete; 3: Brick); $M_{k,j}$ is the use of material k in unit structure j (kg/m^2 or block/m^2; $j = 0$: Frame & shear wall structure; 1: Frame structure); $S_{n,j}$ is the increment of building area with structure j in the nth year; $S_{n,j}$ is the total area of buildings with structure j in the nth year that are still in use (not demolished yet).

CO_2 emissions in the period of construction (${B^{CE}}_{n2}$) are from construction site clearing, materials transportation, and lifting inside the construction site, equipment operation, and electricity consumption. They are given as

$$B_{n,2}^{CE} = \sigma B_{n,1}^{CE} \tag{7}$$

$$\overline{B_{n,2}^{CE}} = \sigma \overline{B_{n,1}^{CE}} \tag{8}$$

where the construction CO_2 emissions coefficient σ is assumed to be 0.1 reference. In this paper for simplicity reasons, we generally combine $B_{n,1}^{CE}$ and $B_{n,2}^{CE}$ to obtain the emissions for materials preparation and building construction.

CO_2 emissions in the period of use and operation (${B^{CE}}_{n3}$) are from central household electric appliance, heating and air conditioning, domestic hot water and necessary building maintenance throughout the building life span. For this stage the realistic emission is

$$B_{n,3}^{CE} = \sum_{l=0} \sum_{m=0} E_{nlm}(n) \times S_{nm} \tag{9}$$

where $E_{nlm}(n)$ is a function modeled by statistics and represents the emissions intensity of utility l ($l = 0$: Heating; 1: Air conditioning; 2: Lighting; 3: Appliance; 4: Domestic hot water; 5: Cooking) in building type m ($m = 0$: Residential building; (1) Small to mid-sized public building; (2) Hotel; (3) Shopping mall; (4) Large office building; (5) Hospital; (6) School; (7) Traffic hub; S_{nm} is the total area in use in the nth year for building type m.

CO_2 emissions in the period of demolition and recycle (${B^{CE}}_{n4}$) are from building deconstruction, transportation, and recycle. However, certain building materials can be recycled at this stage, thus offsetting part of the emissions from ${B^{CE}}_{n1}$. In practice, only steel is widely recycled in China and therefore the emission offset at this stage is given as

$$B_{n,4}^{CE} = -\sum_{j=0} R_0 \times M_{0,j} \times D_{n,j} \tag{10}$$

$$\overline{B_{n,4}^{CE}} = -\sum_{j=0} \frac{R_0 \times M_{0,j} \times S_{n,j}}{N} \tag{11}$$

where R_0 is CO_2 emissions mitigated from recycling steel; $M_{0,j}$ is the amount of steel recycled from unit structure j (kg/m^2; $j = 0$: Frame & shear wall structure; 1: Frame structure); ΔD_{nj} is the area of structure j demolished in the nth year.

Calculation of transportation CO_2 emissions

CO_2 emissions from transportation sectors (T^{CE}) depend on population, travel modes, and travel distances, which can have complex patterns. They can be estimated from local fuel consumption or sample surveys on travel modes and distances. As the data of fuel consumption is difficult to obtain, we use the latter method and data to estimate T^{CE} (Huang et al., 2008; Xiao-lin, 2007). In our case, Lingang is a satellite city of Shanghai, and its adult inhabitants can be divided into four groups according to their travel characteristics: college students (concentrated on or around university campus in the city); local residents (those who live and work in the city), out-commuters (those who live in the city and work outside), and in-commuters (those who live outside and come to the city for work). Thus the transportation CO_2 emissions in the nth year (T_n^{CE}) are calculated as

$$T_n^{CE} = P \times \sum_{i,j,k} (i \times R_j \times L_j \times E_j \times I_k) \tag{12}$$

where i is the percentage of residents with different trip purposes to total residents number; R_j is the percentage of residents with different transportation methods ($j = 1$, private car, $j = 2$, public transportation, $j = 3$, bicycle $j = 4$, walk); L_j is the annual trip distance of different transportation methods; E_j is energy consumption per kilometer of different transportation methods; and I_k is CO_2 emission coefficient of each energy type.

Calculation of CO_2 storage of urban green system

Urban green systems fix a certain amount of carbon each year through the absorption of carbon dioxide. Net CO_2 reserves in urban green areas (G^{CS}) can be estimated by carbon captured in plant biomass (both above-ground and blew-ground biomass), and soil organic matters. In this paper CO_2 reserved by soil is not included because of the lack of research in China. As grass and dead branches are usually cleaned periodically and disposed of in trash or burned, thus returning the carbon to atmosphere, they are excluded from the CO_2 reserves. This leaves shrubs as the major contributor to carbon fixation.

Carbon storage of per unit biomass differs with location, species, and parts of plants, but the differences are small (IPCC, 2006; Chen, 2003). The default value recommended by IPCC can be used when there is a lack of local research data. Guan researched urban CO_2 reserves in Guangzhou, a megalopolis in southern China (Guan et al., 1998). Wang also estimated that urban biomass every year in Beijing increases by 2.09 t/km^2, carbon by 1.12 t/km^2, and CO_2 by 3.68 t/km^2 (Wang, 2009).

The simplified urban CO_2 G^{CS} equation is given as

$$G^{cs} = \sum_{i=0} (S_i \times G_i) \tag{13}$$

where S_i is the area of different green systems, $i = 0$, urban green land, $i = 1$, farm land, $i = 2$, forest; G_i is the amount of CO_2 reserved per unit area of different green systems.

CO_2 mitigation goals for new cities

The total emissions mitigation goals (E^M) are calculated and decomposed as

$$E^M = R^M \times C^E = R_b \times B^{CE} + R_t \times T^{CE} - R_g \times G^{CS} \tag{14}$$

where R^M is the total mitigation ratio; R_b, the mitigation ratio of building emissions; R_t, the mitigation ratio of transportation emissions; R_g, the growth rate of urban green systems. How to set the R^M relies on the respective case areas and local policies.

Ambition, technology, and demographics

Different cities usually set different mitigation ratios according to local environments. The case study of Lingang would show its goal set procedure in the paper.

New cities share the common similarities with developed cities, yet own several distinguished characters. Firstly, the growth ratio of population, land use, and economy is much bigger than developed cities; Secondly, the data of a new city are hard to access, which is constrain for the research, but predicting data or planning data can be used as an alternative way. Thirdly, the demographic character could be largely different from developed cities. Take Lingang as an example, most of the citizens in Lingang are university students and young workers. Fourthly, application of new technology is easier in new cities, and it is an obvious opportunity for low carbon planning.

Case study

Introduction in Lingang

Lingang is a new satellite city of Shanghai, China. A coastal city facing the East China Sea, its average temperature is between 13°C and 20°C, and average annual rainfall is between 800 mm and 1600 mm. The development of Lingang was started in 2003, and today the young city is under full-bloom construction and built as a demonstrative Low-Carbon Zone of Shanghai. The infrastructure and population will achieve the planning goals in 2020. Central area of Lingang new city (hereinafter referred to as ''Lingang City Centre'') is the subject of this case study, covering an area of 70 km^2 and having a population of about 50,000 in 2010. Figure 2 shows Lingang's integrated business, service, and living area without any industries planned. Lingang City Centre, shared a lot of same demographic characters with the whole City of Lingang, was the calculation scope and low carbon planning target in this paper. Without additional explanations, emission factors of Lingang were equal to those of Lingang City Centre.

This research assumed that Lingang and Shanghai shared the same per capita GDP, which increased rapidly since China's reform and opening up in 1978. Its per capita GDP reached 80,000 RMB in 2010 and was expected to grow at a similar rate as that of Shanghai (Figure 3).

Assessment of CO_2 emissions in 2020-business as usual scenario

Building sector. The development of Lingang City Centre started in 2003 and would finish in 2020. All public and residential buildings in this case were concrete buildings with a life span of 50 years. Upon demolition, 90% of steel will be recycled. The emission factors of these buildings were obtained through analysis and forecast after local investigation and literature

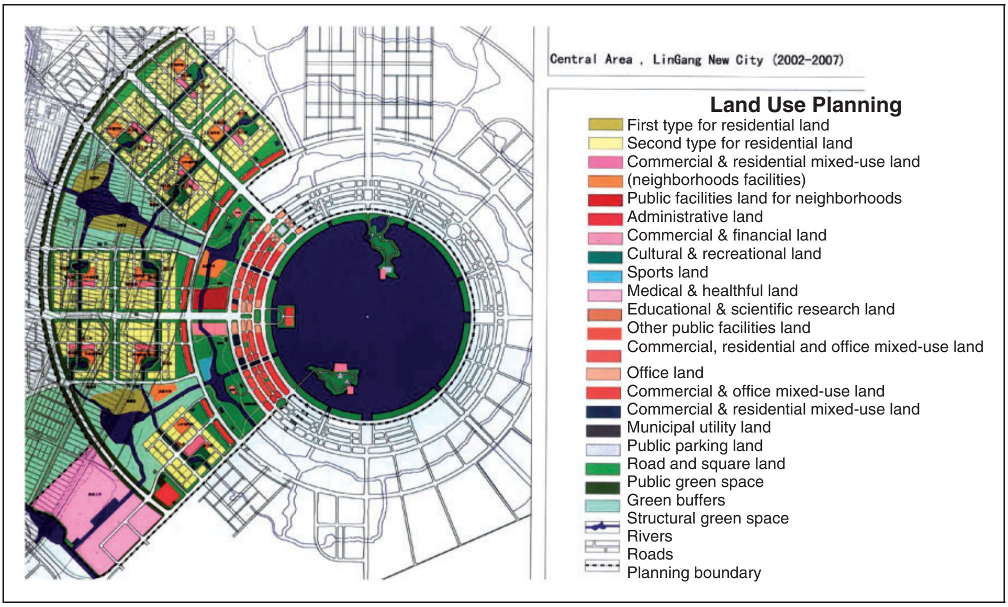

Figure 2. Control detailed planning on the first stage of Lingang City Centre (2002–2007).

research. The CO_2 emission factors for four stages of public and residential buildings are shown in Table 1 and 2.

Two methods were used to calculate building CO_2 emissions of B^{CE}. First we took the most straightforward approach and calculated B^{CE} as they were occurring, or the realistic emissions, according to equations (3.1) to (3.4). As shown in Figure 5 and 6, the emissions for the materials production and construction ($B_1^{CE} + B_2^{CE}$) would remain stable before the year 2020, and then will become zero after that. The emissions at this stage for public buildings were about 200,000 tones each year, compared to about 400,000 tones for residential buildings. This was because the residential buildings were the main building types each year (Table 3). Emissions at the demolition stage (B_4^{CE}) would remain zero for the time frame (2006–2025) since there would not be any demolitions until the year 2053 or so. B_3^{CE}, and the emissions during the use and operation stage, represent the major emissions for both types of buildings (Figure 4(a) and 4(b)). It was noted that for public buildings, on average the emission factors at this stage were about 1.5 times higher than that of residential buildings.

The next approach represented a method more meaningful for setting emission reduction goals. Here we averaged the emissions incurred in the preparation, construction, and

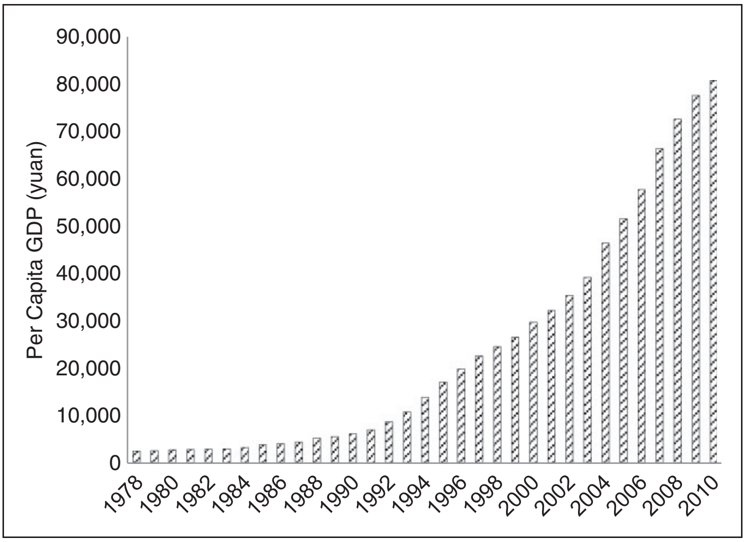

Figure 3. Per capita GDP of Lingang City Centre from 1978 to 2010. Source: Shanghai census data.

Table 1. Emission factors on production and transportation, construction, deconstruction and disposal of Lingang City Centre (kg CO_2/m^2).

	Public buildings	Residential buildings
Production and transportation	5.6	5.6
Construction	400	400
Deconstruction	2.52	2.52
Disposal and recycle saves	99.01	100.56

Source: Jiang and Wu (2010).

Table 2. Prediction of emission factors on building use of Lingang City Centre (kg $CO_2/m^2 \cdot a$).

Year/building types	Public buildings	Residential buildings
2006	47.63	32.14
2007	49.99	33.55
2008	52.34	35.17
2009	54.69	36.79
2010	57.04	38.41
2011	59.39	40.03
2012	61.74	41.65
2013	64.09	43.27
2014	66.44	44.89
2015	68.79	46.51
2016	71.14	48.13
2017	73.49	49.75
2018	75.84	51.37
2019	78.19	52.99
2020	80.54	54.61
2021	82.89	56.23
2022	85.24	57.85
2023	87.59	59.47
2024	89.94	61.09
2025	92.29	62.71

Source: Jiang and Wu (2010).

Table 3. Area of planning, construction, and floor of Lingang City Centre from 2006 to 2025 (km^2).

		2006	2010	2015	2020	2025
Planning area		68.58	68.58	68.58	68.58	68.58
Construction land area		14.33	28.66	42.99	57.32	57.32
Floor area	Public buildings	2.47	4.94	7.42	9.89	9.89
	Residential buildings	4.75	9.51	14.26	19.01	19.01

demolition stages over the life span of the building. Figure 5(a) and (b) shows these averaged CO_2 emissions (i.e. $\overline{B_1^{CE}} + \overline{B_2^{CE}} + \overline{B_3^{CE}} + \overline{B_4^{CE}}$) together with $B^{CE}{}_3$ (LCA CO_2 emissions).

Regardless of either calculation method, the largest amounts of CO_2 emissions both in public buildings and residential buildings were emitted in the usage period. In this period, CO_2 emissions of public building were mainly from heating, air conditioning, lighting, and equipment; CO_2 emissions in residential building were mainly from household electric appliance, heating and air conditioning, domestic hot water, and necessary building maintenance. Different detailed strategies were developed in the light of characteristics in every period.

Transportation sector. Residents in Lingang City Centre could be divided into four groups according to their travel characteristics and distances: students, local residents,

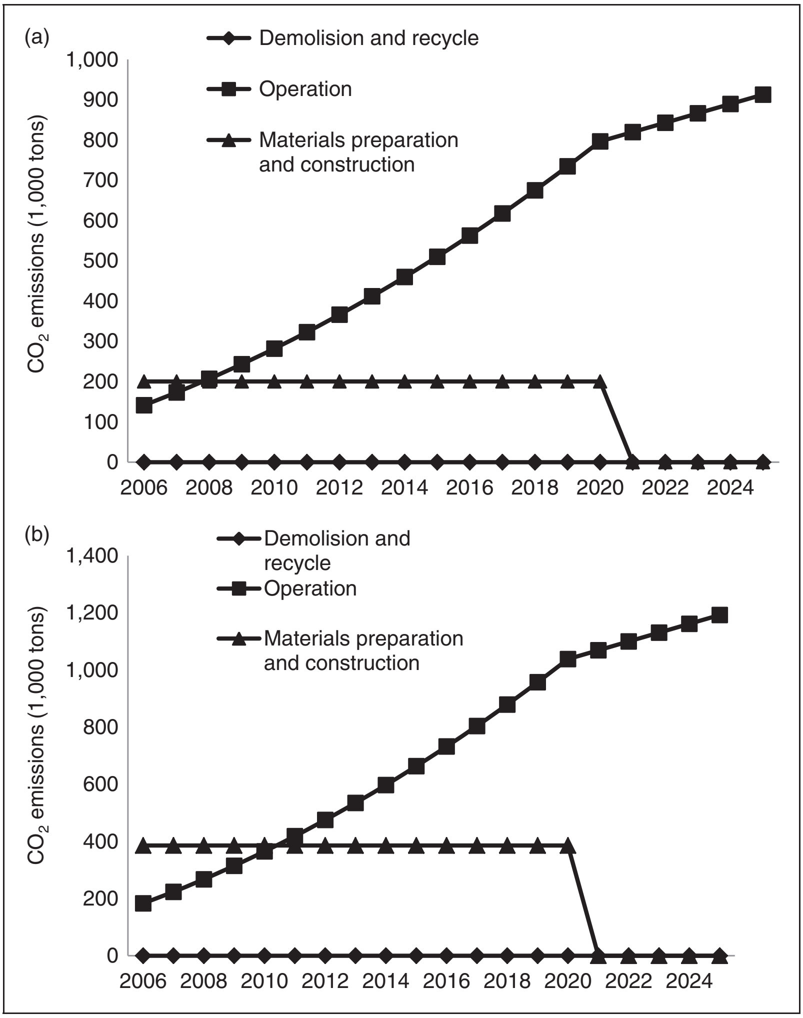

Figure 4. (a) Realistic CO_2 emissions from public buildings of Lingang City Centre. (b) Realistic CO_2 emissions from residential buildings of Lingang City Centre.

out-commuters, and in-commuters (see "Methods" section for details). There were only 50,000 inhabitants in Lingang City Centre by the end of 2010, among them 48,000 were college students, 100 local residents, and 2000 in-commuters (Table 4). It was planned that the population would reach 400,000 by the year of 2025. The number of college students would remain the same, and other types of inhabitants would increase as shown in Table 4.

Each type of residents was assumed to use different transportation modes and habits. College students had a smaller activity range compared to local residents, the per capita transportation CO_2 emissions of college students can be considered to be half of average level of residents in Shanghai. Both local students and local residents worked and lived in Lingang and traveled to Shanghai center on weekends, the per capita transportation CO_2 emissions of these two citizens could be considered to be the sum of average emissions of residents in Shanghai and emissions from traveling to Shanghai on weekends. The other two types of residents needed to commute from Shanghai to Lingang every day. Surveys showed

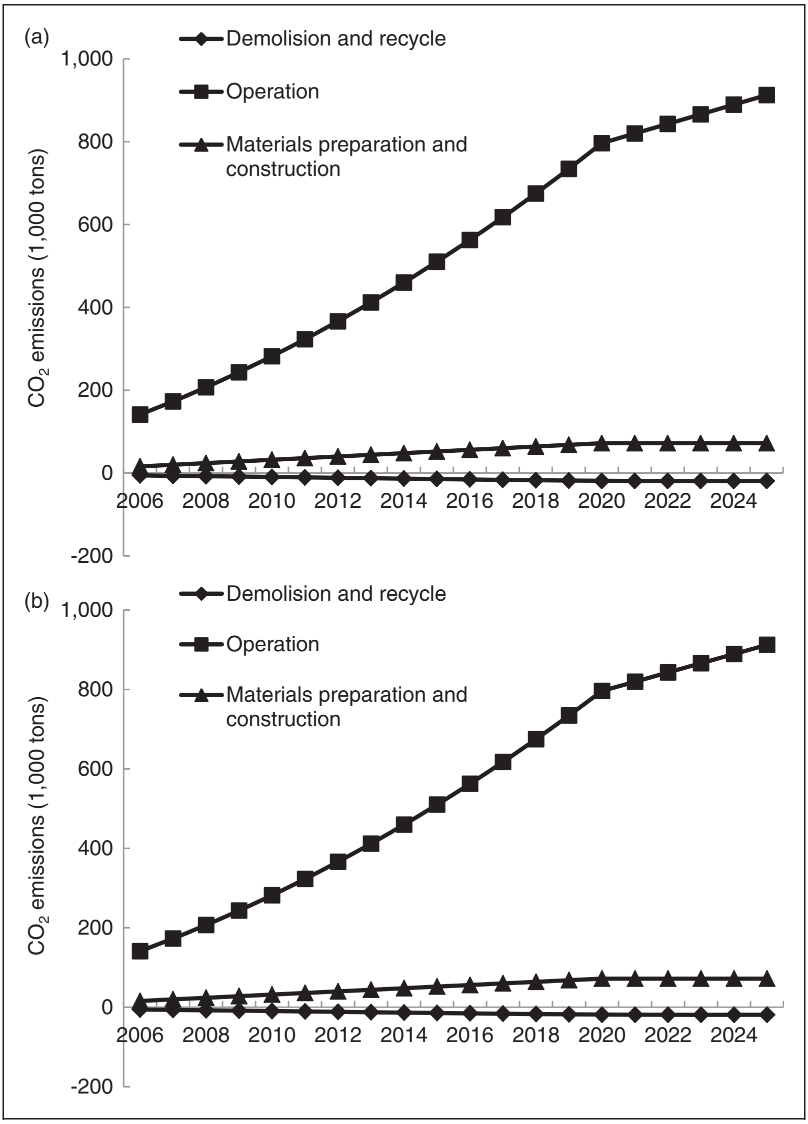

Figure 5. (a) LCA CO_2 emissions from public buildings of Lingang City Centre. (b) LCA CO_2 emissions from residential buildings of Lingang City Centre.

that their major transport modes are shuttle buses and private cars, and part of these residents would choose subway after it was opened in 2012. Assuming there were 20 persons in one shuttle bus and 1.5 persons in one private car every time on average, while the distance from Lingang City Centre to Shanghai city centre was roughly 70 km.

Shanghai's average CO_2 emissions from different transport modes were needed to aid in the calculation in Lingang. According to Zhao et al. (2009), Shanghai's average CO_2 emissions from different transport modes per hundred kilometers are shown in Table 5.

Based on annual travel records of four commuter vehicles and population from 2001 to 2009 in Shanghai, the annual per capita CO_2 emissions in Shanghai can be estimated (Table 6).

Table 4. Residents of Lingang City Centre from 2010 to 2030.

	2010	2015	2020	2025	2030
College students	48,000	48,000	48,000	48,000	48,000
Local residents	100	58,800	117,400	176,000	176,000
Citizens who work in Lingang and live in Shanghai	2,000	30,700	59,300	88,000	88,000
Citizens who work in Shanghai and live in Lingang	0	29,400	58,700	88,000	88,000
Total	50,100	166,800	283,400	400,000	400,000

Table 5. Per capita CO_2 emissions from different transport modes in Shanghai (tones/a).

Shuttle bus	Private car	Subway
2.72	6.67	0.18

Source: Zhao et al. (2009).

Table 6. Per capita transportation CO_2 emissions of Shanghai and Lingang locals (excludes travels between Shanghai and Lingang on weekends) (kg/a).

Year	2010	2011	2012	2013	2014	2015	2016	2017
	623	668	713	758	804	849	894	940
Year	2018	2019	2020	2021	2022	2023	2024	2025
	985	1030	1075	1121	1166	1211	1257	1302

Source: Shanghai Municipal Statistics Bureau (2010).

After calculations according to function (12) and above assumptions, Lingang City Centre's per capita CO_2 emissions was 488 kg in 2010, while Shanghai city's per capita CO_2 emissions was 623 kg at the same time. With the rapid growth of population, Lingang City Centre's transportation CO_2 emissions and per capita CO_2 emissions would have a corresponding growth and the per capita CO_2 emissions of Lingang would be higher than that of Shanghai before 2025 (Figure 6).

With the sharply increasing population, transportation will be responsible for about 20 percent of total emissions in 2020. Urban areas rely heavily on transportation networks of various kinds for both internal and external movements. Intercity metro from Shanghai City Centre to Lingang City Centre will be open in 2012, then it is assumed that one-third of workers will transfer to subway from private cars and shuttle buses. In this way, the transportation CO_2 emissions will decrease 2,000,000 ton every year. This contributes a lot in the development of low carbon city. After population stability of Lingang City Centre in 2025, the total 2025 transportation CO_2 emissions will be around 1,000,000 ton/a and it would increase slowly after that. Per capita CO_2 emissions is 2.33 t/a (twice as that of Shanghai city), which is due to the large proportion of inhabitants who commute between these two cities every day.

Urban green system. The green land rate ranges from 30% to 50% according to Lingang's plan. When green land rate is 30%, urban green reserves 5,000 ton CO_2 annually after the

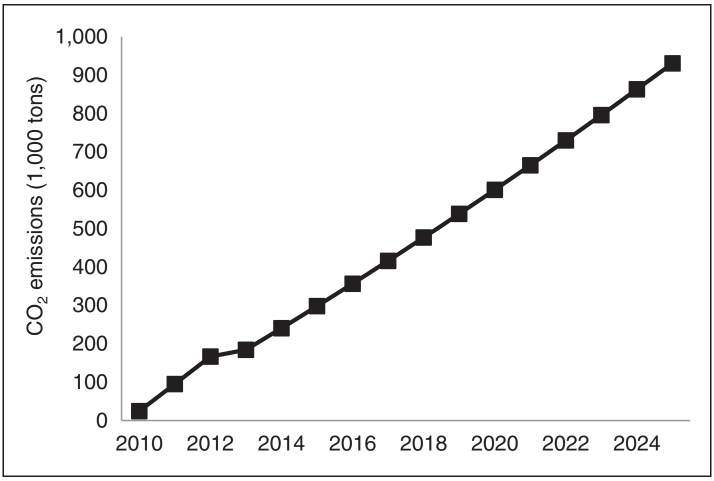

Figure 6. Transportation CO_2 emissions of Lingang City Centre.

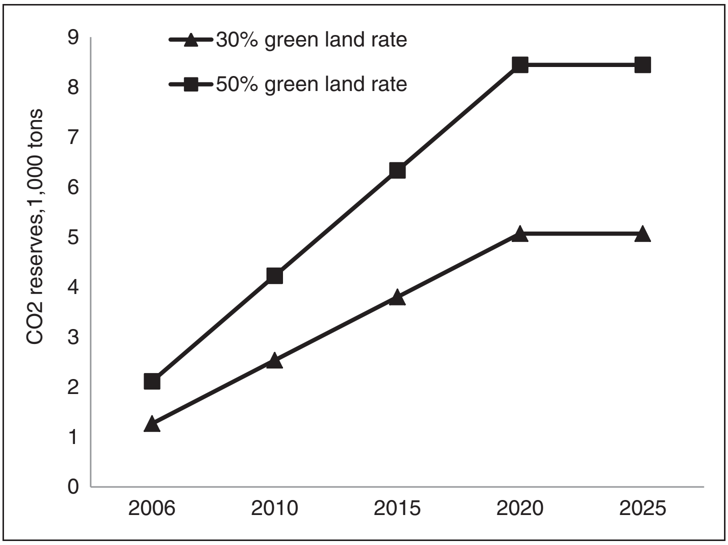

Figure 7. Urban green CO_2 reserves of Lingang City Centre.

completion of construction in 2020; and when green land rate is 50%, urban green reserves 8,000 ton CO_2 annually after the completion of construction in 2020 (Figure 7).

The urban green system has inconspicuous carbon reserve effect with the huge amount of CO_2 emissions due to building operation and traffic. Nevertheless, appropriate planning and management of urban green system could reduce the Lingang City Centre's CO_2 emissions indirectly by orientating the residents towards Green life and lowering ambient temperature by shading. The green system is very important for the development of urban area due to its vital ecological adjustment and aesthetic function besides carbon fixation ability.

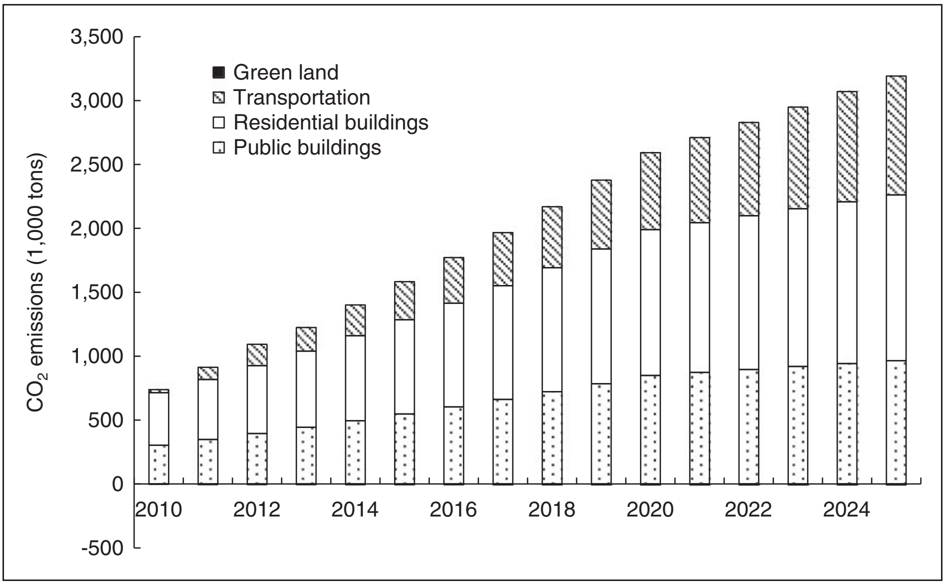

Figure 8. Assessment of total CO_2 emissions of Lingang City Centre (2006–2020).

Assessment of Lingang's CO_2 emissions

Total CO_2 emissions. Among the three components of Lingang's carbon model, building sector, transportation sector and urban green system, building sector emitted the largest amounts of total CO_2 emissions. In order to analyze carbon emissions characters and set a detailed mitigation goal, public building emissions and residential building emissions were calculated separately. Applying LCA to this assessment, CO_2 emissions from raw materials, construction, and demolish were equally distributed to building life cycle extends (50 years). Accordingly, the total CO_2 emissions of Lingang City Centre were around 1,000,000 tons in 2010, almost entirely from building sector. However, as the population exploded in the following years and suburb transport modes, CO_2 emissions from transportation sector increase rapidly from 2010 to 2020. Green system CO_2 reserves can counteract part of CO_2 emissions, but this offset is not significant, only account for about 1% of total urban CO_2 emissions (Figure 8).

CO_2 emissions inventories in 2010 were public buildings, 304,000 tons, residential buildings, 410,000 tons, transportation, 24,500 tons, and green system, −3,380 tons. In 2020 CO_2 emissions inventories will be public buildings, 850,000 tons, residential buildings, 1,140,000 tons, transportation, 601,000 tons, and green system, −6,760 tons (Figure 9). After the completion of construction and stable population in 2020, CO_2 emissions will increase moderately. The 2020 emission levels can be set as the mitigation baseline.

Lingang, as a young and rapid developing urban area, has a unique carbon emissions characteristic: high grow speed for each carbon emissions sector. According to the graphic above, the building carbon emissions increases three times in 10 years while that of traffic grows 30 times due to the population explosion. To achieve the objective of 50% reduction in carbon emissions, public building, residential building as well as public transformation should be taken as the key factor in the low carbon planning. Besides, waste discharge, policy making and executing, education, and design strategy suitable for the Climate change should also be considered.

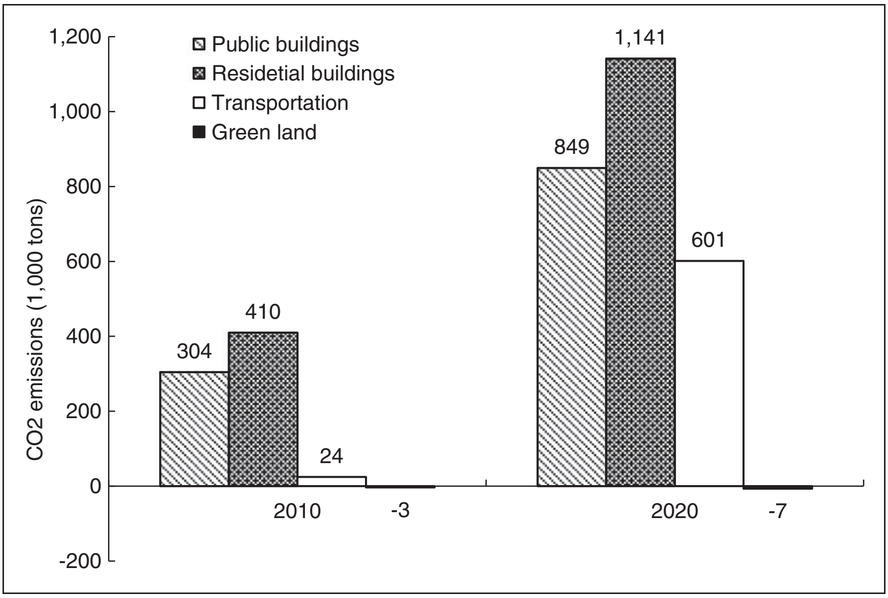

Figure 9. The 2010 and 2020 CO_2 emissions of Lingang City Centre.

Table 7. CO_2 emissions mitigation goals of certain cities in EU and USA.

Cities	Goals
Portland	In 2007, Portland City Council adopted resolutions directing staff to design a strategy to reduce greenhouse gas emissions 80 percent by 2050, 40 percent by 2030.
Los Angeles	Los Angeles will meet the goal of reducing CO_2 emissions 35% below 1990 levels by 2030.
Miami	Miami planned to reduce greenhouse gas emissions to 25% below 2006 levels citywide by 2020 and to 25% below 2007 governmental levels by 2015
Chicago	Chicago's goal is to reach an 80% reduction in GHG emissions from 1990 levels by 2050, reach an 25% (24.2 MMTCO2) reduction in GHG emissions from 1990 levels by 2020
Boulder	According to Kyoto Goal, Boulder planned to reduce GHG emissions by 350,000 metric tons of mtCO2e from 2004 levels by 2012.
More than 400 towns and cities in EU	According to European Covenant of Mayors, covenant signatories aim to meet and exceed the European Union's 20% CO_2 reduction objective by 2020.

Source: City of Berlin (2011), City of Boulder (2006), City of Chicago (2008), City of London (2010), City of Los Angeles (2007), City of Portland and Multnomah County (2009), Grand Paris Seine Ouest (2011), Miami (2008).

CO_2 emissions mitigation goals

CO_2 emissions mitigation goals of certain cities in EU and USA are listed in Table 7, indicating mitigation status of the developed cities.

Figure 10 lists four scenarios of Lingang emissions taking Shanghai as a reference. As Lingang is one of three "low carbon demonstrative districts" in Shanghai city, ought to set a

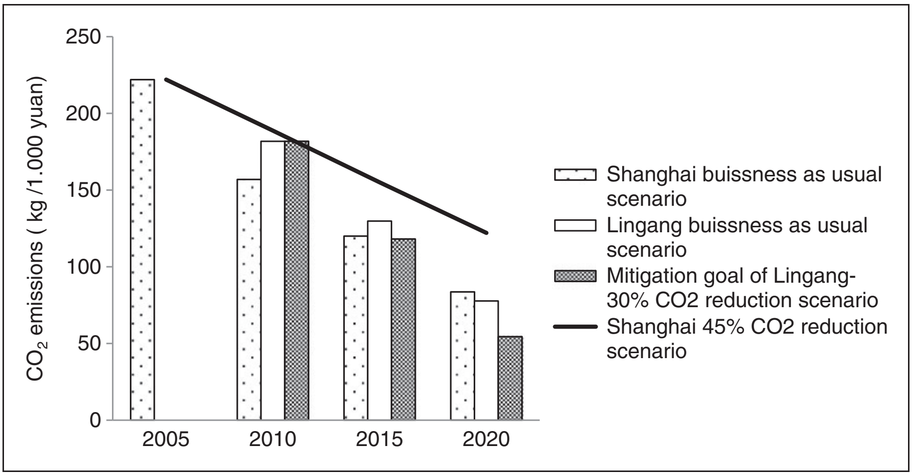

Figure 10. Assessment of CO_2 emission intensity in Linggang City Centre under four scenarios.

Table 8. CO_2 reduction goal of Lingang City Centre.

	CO_2 emissions in 2010	CO_2 emissions in 2020	CO_2 reduction goals in 2020
Total CO_2 emissions (ton)	735,000	2,585,200	−30%, 1,809,700
CO_2 emission intensity (kg/1,000 yuan)	182	78	−30%, 54

more ambitious mitigation goal than City of Shanghai. The target that Lingang City Centre reduces both 30% CO_2 emission amounts on 2020 levels fulfill technical feasibility and position as a low carbon city. However, not similar to relatively mature cities, Lingang City Centre is a fast growing town, both in population and building areas, thus needing its more reasonable mitigation objectives. Hence, the emission amount in the year of 2020 is considered as baseline for calculating mitigation when all the building constructions would be finished, instead of current status.

Based on the analysis above, according to the goal of CO_2 reduction in Lingang City Centre, there will be 30% decrease in CO_2 emissions than the estimated level by 2020, which means the CO_2 emissions intensity would be reduced by 230 kg/10,000 yuan and the total local CO2 emissions would be reduced by 780,000 ton (Table 8). In order to achieve this goal, all the significant sectors need to set their detailed objectives and strategies for reduction in CO_2 emission (Table 9).

CO_2 emission mitigation strategies

Mitigation strategies were planned according to the inventory of sector emissions and available technology and resources. As shown in Table 10, strategies in building sector covered the four phases of life time. First, by improving the standards of building materials and transportation efficiency, reducing building CO_2 emissions by 10% in 2020 in the period of construction and transportation. Second, implementing green and low

Table 9. CO_2 reduction objectives of each sector in Lingang City Centre (tones).

Sectors	CO_2 emissions in 2010	CO_2 emissions in 2020	CO_2 reduction goals in 2020
Public buildings	304,400	849,400	−35%, 552,100
Residential buildings	409,800	1,141,400	−35%, 741,900
Transportation	245, 00	601,200	−20%, 481,000
Green space	−3,400	−6,800	0% −0.68

Table 10. CO_2 mitigation strategies in building, transportation, and green land sectors.

1. Building and energy	Reduce 35%[a]	
1.1 Production and transportation	Reduce 10%	Improving the standards of building materials and transportation efficiency
Concrete	Reduce 10%	
Steel	Reduce 10%	
1.2 Construction	Reduce 10%	Implementing green and low impact construction management
Concrete	Reduce 10%	
Steel	Reduce 10%	
1.3 Use and operation	Reduce 40%	New energy adoption and energy efficiency improvement
Heating	Reduce 50%	
Air conditioning	Reduce 50%	
Lighting	Reduce 20%	
Electric appliance	Unchanged	
Domestic hot water	Reduce 50%	
Cooking	Unchanged	
1.4 Demolition and recycle	Reduce 10%	Recycling
Concrete	Reduce 10%	
Steel	Reduce 10%	
2. Transportation Reduce 20%		
2.1 Improve local residents (both work and live in Lingang City Centre) to account for 60% by improving conditions of living and office		
2.2 Support public transit of intercity and intracity		
2.3 Reduce per capita daily vehicle miles (VMT)		
3. Green lands		
3.1 Minimum ratio of green space is 30%		
3.2 Maximum ratio of manual shaving lawn is 20%,		
3.3 Trees and shrubs may not be less than 70% in green lands		
3.4 Reduce heating demand by introducing natural lights into building and design wind tunnels		
3.5 Plan continuous green lands for activities and non-motorized travels		

[a]All the reduction baselines based on 2020 emission levels.

impact construction management to reduce CO_2 emissions by 10% in 2020 during the period of construction. Third, reducing CO_2 emissions by 39% in 2020 in the period of usage of building through new energy adoption and improvement in energy efficiency. Last, reducing CO_2 emissions by 10% in 2020 in the period of deconstruction by recycling.

Strategies in transportation sector include improving local residents (both work and live in Lingang City Centre) 60% by improving conditions of living and office; supporting public transit of intercity and intracity; and reduce the miles of per capita daily vehicle below current levels by 2020.

Strategies in urban green systems include setting the minimum ratio of green space is 30%; the ratio of manual shaving lawn not exceeding 20% while that of trees and shrubs may not be less than 70% in green lands; reducing heating by introducing more sunshine into building and appropriate layout of wind tunnels; making continuous green lands which would be convenient for activities and non-motorized travels such as walking and bicycle riding.

Discussion and conclusions

In this paper, an integrated analysis method for assessment and mitigation of urban carbon dioxides of new cities in China was proposed. LCA method was included into the analysis to make the emission inventory comprehensive. To demonstrate this method, we quantitatively evaluated the present and future carbon emissions of Lingang. In addition, based on the prediction of the demographics of the new cities and referred for carbon emissions reduction target of Chinese government and that of cities in developed countries, a reasonable carbon emission reduction target for the new city has been made. Technical measures and policy for carbon emissions reduction have also been suggested and effective regulation is recommended for local government to make sure the carbon emissions reduction target could be reached.

The case study of Lingang showed that building construction and operation was the largest carbon emission sector in new cities. Transportation was secondary contribution sector, and landscape did not contribute to large extent in a new city's carbon inventory. CO_2 emissions mitigation distribution strategies could be developed in the three sectors: Strategies in building sector were divided into four stages: production and transportation, construction, operation, and deconstruction; strategies in transportation sector included improving conditions of living and office, supporting public transit of intercity and intracity; and reducing per capita daily vehicle miles; strategies in urban green systems included setting the minimum ratio of green space, the maximum ratio of manual shaving lawn and minimum ratio of trees and shrubs, and planning continuous green lands which would be convenient for green traffic way such as walking and bicycle riding.

The work shown in this paper has the following contributions: one of the earliest quantitative carbon mitigation studies for new cities; the local data were used rather than simply citing data from abroad with more accurate results; carbon emissions for the coming 10 years were also predicted in addition to the estimation of current carbon emissions.

Due to the lack of measured data, the accuracy of the proposed carbon emission method can't be assessed currently. This problem is expected in the actual measured data which can be used to calibrate the parameters involved in this method in future, so that more accurate result can be obtained.

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