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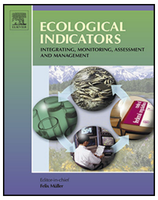

A model for developing a target integrated low carbon city indicator system: The case of Xiamen, China

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ABSTRACT

Carbon intensity targets, namely carbon emissions per unit of GDP, are used as macro-level indicators of low carbon performance at the province- and city-level in China. However, this measure is too aggregated to provide a meaningful indication of low carbon performance and inform practical management strategies. Most traditional low carbon city indicators have no direct relationship with national carbon intensity reduction targets and do not provide municipal government administrators with the practical information they need to inform low carbon development at the local level. This paper integrates city-level carbon intensity targets with a low carbon city indicator system by means of a decomposed method to offer a better approach for carbon intensity reduction performance evaluation. Using Xiamen as a case study, one of the NDRC's low-carbon project areas, a target integrated indicator system is presented, including indicator values which have been determined through scenario analysis and calculation. The indicators and values can help local municipal governments to meet their carbon intensity reduction targets by providing an indication of current performance and identifying sectors where there is scope for further improvement. The methodology provides the theoretical basis and reference values for the evaluation of a city's low carbon performance within the context of achieving a carbon reduction target, thereby enhancing the potential for scientific and operational evaluation at the local level.

1. Introduction

Low carbon city development has become a topic of global interest in recent years (Kennedy et al., 2011; Lin et al., 2010). China has pledged to reduce its carbon intensity (CO_2/unit of gross domestic product (GDP)) by 40–45% by 2020 from 2005 baseline levels. As a developing country, there still have a long way to reach the absolute decoupling for China, and the emissions of GHG will inevitably continue to grow on the context of rapid urbanization and industrialization. Not until 2030, the absolute decoupling target may be reached (He et al., 2012). Therefore, in the short term, the relative decoupling target (intensity target) is still useful to control the increasing rate of carbon emissions, though it cannot decrease the total emissions. The Chinese government has included the 40–45% reduction goal in its 12th Five-Year Plan on Social and Economic Development (FYP), which covers the period from 2011 to 2015. As part of this plan, the carbon intensity reduction target has been made a binding target for provinces (China State Council, 2011) and this will soon also be extended to cities. In addition, the NDRC launched a national low carbon province and low carbon city pilot project in 2010, which requires chosen pilot areas to meet this reduction target. This results in an urgent need to develop effective carbon intensity reduction measures and to track progress in meeting these targets for Chinese cities.

Low carbon indicator systems are an important component of integrated environmental management, which can help to evaluate current performance and measure progress toward set targets. Some researchers prefer to develop comprehensive indicator system to evaluate low-carbon development from different dimensions. The Regions for Sustainable Change (RSC) project developed a low carbon indicator toolkit, which is a complex and comprehensive tool for stakeholders from European regions who need to work with low carbon indicators in the policy-making process. Chatham House and Chinese Academy of Social Sciences (2010) developed 12 indicators for assessing low carbon development, belonging to four categories: low carbon productivity, low carbon consumption, low carbon resources, low carbon policy. The World Bank recommended a low-carbon indicator list for Chinese cities, including five categories: carbon emissions, energy, green buildings, sustainable transport, and smart urban form (Baeumler

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et al., 2012). Other researchers try to construct low carbon index by integrating different selected indicators for the evaluation of relative low carbon city status and promoting low carbon city development. Song established an index analysis system to evaluate the low carbon city development in the Yangtze River Delta based on the driving force-pressure-state-impact-response (DPSIR) model and factor analysis (Song and Li, 2012). Yang established a three-layer low carbon city evaluation index system and calculated a comprehensive evaluation score of Beijing's low carbon city development in 2009 (Yang et al., 2011). And some similar weighted multi-layer index system was also proposed by other Chinese researchers (Li et al., 2011; Yan et al., 2011; Zhang and Wang, 2010). To avoid that macro-level indicator may be too aggregated to be meaningful measurements of low carbon development, Price developed a sectoral end-use low carbon indicator system at the provincial and city level for China (Price et al., 2013).

For Chinese intensity reduction target, most above approaches leave a crucial gap in effective performance evaluation as these indicators had not direct relationship with individual reduction target. This prevents local government administrators from using such indicator systems in their management of urban carbon intensity reduction and evaluating progress in relation to the binding target. This paper attempts to fill this research gap by integrating the carbon intensity reduction target into the indicator system. This type of low carbon city indicator system will allow municipal government administrators to understand performance trends, measure current performance, respond with timely policy adjustments and track progress leading up to national carbon intensity reduction target deadlines.

This paper is organized as follows: (1) calculating low carbon indicators through the decomposed method; (2) constructing the integrated indicator system; (3) taking Xiamen city as an example to illustrate the target integrated indicator system and discussion; (4) conclusions.

2. Low carbon city indicator selection by decomposed method

Energy use, industrial processes and product use, agriculture, forestry and other land use, and waste are included in GHG inventory calculations according to IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The calculation of energy use, industrial processes, agriculture, forestry and waste has been carried out according to the NDRC guidelines for provincial GHG inventories (NDRC, 2010). According to NDRC's guidelines, only these five components of non-embodied GHG emissions are currently monitored and managed by local government. In this paper, the emissions of energy use, industrial processes, agriculture, forestry, waste are considered, and the emissions of product use and other land use are not included. It is worth to mention that an only Scope 1 + 2 emission is under consideration according to the WRI/WBCSD's Greenhouse Gas Protocol (WRI/WBCSD, 2004) in this paper. Furthermore, the Chinese central government uses carbon intensity as the measure for the binding target for Chinese provinces and cities. Thus, we begin by decomposing the aggregate GDP intensity of GHG emissions as follows:

$$\begin{aligned}\frac{CE_{total}}{GDP} &= \frac{CE_{energy}+CE_{waste}+CE_{agriculture}+CE_{industraial\ process}+CE_{forest}}{GDP}\\ &= \frac{CE_{energy}}{GDP}+\frac{CE_{waste}}{GDP}+\frac{CE_{agriculture}}{GDP}+\frac{CE_{industraial\ process}}{GDP}\\ &\quad +\frac{CE_{forest}}{GDP}\end{aligned} \tag{1}$$

where, CE_{total} is total carbon emissions in one year; GDP is gross domestic product in one year; CE_{energy} is carbon emissions by energy use; CE_{waste} is carbon emissions by waste disposal; $CE_{agriculture}$ is carbon emissions from agriculture; $CE_{industrial\ process}$ is carbon emissions from industrial process; CE_{forest} is carbon emissions from forests.

Eq. (1) means the total GHG emission intensity is decomposed into five parts: energy use intensity, waste intensity, agriculture intensity, industrial process intensity, and forest intensity. Each part of Eq. (1) will be further discussed in the sections below.

2.1. Energy use

Energy-related GHG emissions are directly related to energy consumption intensity and integrated emission factors. It can be written as follows:

$$\frac{CE_{energy}}{GDP} = \frac{CE_{energy}}{E}\times\frac{E}{GDP} = EF_{integrated}\times I_{integrated} \tag{2}$$

where, CE_{energy} is carbon emissions from energy use; GDP is gross domestic product in one year; E is total energy consumption in one year; $EF_{integrated}$ represents the integrated energy use emission factor; $I_{integrated}$ represents the total energy intensity.

The integrated emission factor in Eq. (2) is determined by the primary energy use structure. This paper only discusses coal, refined oil, natural gas, imported electricity and other non-fossil energy to match the scope of this research.

$$\begin{aligned}EF_{integrated} &= \frac{CE_{energy}}{E}+\frac{CE_{coal}}{E}+\frac{CE_{oil}}{E}+\frac{CE_{natural\ gas}}{E}\\ &\quad +\frac{CE_{imported\ electricity}}{E} = \frac{CE_{coal}}{E_{coal}}\times\frac{E_{coal}}{E}+\frac{CE_{oil}}{E_{oil}}\times\frac{E_{oil}}{E}\\ &\quad +\frac{CE_{natural\ gas}}{E_{natural\ gas}}\times\frac{E_{natural\ gas}}{E}+\frac{CE_{imported\ electricity}}{E_{imported\ electricity}}\\ &\quad \times\frac{E_{imported\ electricity}}{E} = EF_{coal}\times P_{coal}+EF_{oil}\times P_{oil}\\ &\quad +EF_{natural\ gas}\times P_{natural\ gas}+EF_{imported\ electricity}\\ &\quad \times P_{imported\ electricity}\end{aligned} \tag{3}$$

Constrained to:

$$P_{coal}+P_{oil}+P_{natural\ gas}+P_{imported\ electricity}+P_{non-fossil}=1 \tag{4}$$

where, CE_{coal}, CE_{oil}, $CE_{natural\ gas}$ and $CE_{imported\ electricity}$ are carbon emissions from the dominant energy mix, including coal, oil, natural gas and imported electricity; E_{coal}, E_{oil}, $E_{natural\ gas}$ and $E_{imported\ electricity}$ are energy consumption per energy source, including coal, oil, natural gas and imported electricity; EF_{coal}, EF_{oil}, $EF_{natural\ gas}$ and $EF_{imported\ electricity}$ are the carbon emissions factors per energy source, including coal, oil, natural gas and electricity; P_{coal}, P_{oil}, $P_{natural\ gas}$ and $P_{imported\ electricity}$ are the proportion of each energy source in the overall energy mix, including coal, oil, natural gas and electricity.

The energy intensity in Eq. (2) is related to the energy consumption of each sector. The sectors are divided into three productive sectors and household in Chinese statistical records, as follows:

$$\begin{aligned}I_{integrated} &= \frac{E}{GDP}\\ &= \frac{E_{primary\ industry}+E_{secondary\ industry}+E_{tertiary\ industry}+E_{household}}{GDP}\\ &= \frac{E_{primary\ industry}}{GDP}+\frac{E_{secondary\ industry}}{GDP}+\frac{E_{tertiary\ industry}}{GDP}\times\frac{E_{household}}{GDP}\\ &= \frac{E_{primary\ industry}}{GDP_{primary\ industry}}\times\frac{GDP_{primary\ industry}}{GDP}+\frac{E_{secondary\ industry}}{GDP_{secondary\ industry}}\end{aligned}$$

$$\times \frac{GDP_{secondary\ industry}}{GDP} + \frac{E_{tertiary\ industry}}{GDP_{tertiary\ industry}} \times \frac{GDP_{tertiary\ industry}}{GDP} + \frac{E_{household}}{Pop_{city}} \times \frac{Pop_{city}}{GDP} = I_{primary\ industry} \times P_{primary\ industry} + I_{secondary\ industry} \times P_{secondary\ industry} + I_{tertiary\ industry} \times P_{tertiary\ industry} + I_{household} \div GDP_{per\ capita} \quad (5)$$

Constrained to:

$$P_{primary\ industry} + P_{secondary\ industry} + P_{tertiary\ industry} = 1 \quad (6)$$

where, E is total energy consumption in one year; GDP is gross domestic product in one year; $E_{primary\ industry}$, $E_{secondary\ industry}$ and $E_{tertiary\ industry}$ are energy consumption of three productive industry sectors; $GDP_{primary\ industry}$, $GDP_{secondary\ industry}$ and $GDP_{tertiary\ industry}$ are the value-added of each productive sector's GDP output; $I_{primary\ industry}$, $I_{secondary\ industry}$ and $I_{tertiary\ industry}$ represent the energy intensity of each industry; $P_{primary\ industry}$, $P_{secondary\ industry}$, and $P_{tertiary\ industry}$ are the percentage of each industry in the overall economy. As for the non-productive sector, $E_{household}$ is the energy consumption of household, and $I_{household}$ represents household energy consumption per capita; Pop_{city} is the population of the city, and $GDP_{per\ capita}$ is the city's gross domestic product per capita.

2.2. Waste disposal

The emission of waste disposal includes solid waste and waste water, so they can be decomposed into two parts:

$$\frac{CE_{waste}}{GDP} = \frac{CE_{solid\ waste}}{GDP} + \frac{CE_{waste\ water}}{GDP} = \frac{CE_{solid\ waste}}{Pop_{city}} \times \frac{Pop_{city}}{GDP} + \frac{CE_{waste\ water}}{Pop_{city}} \times \frac{Pop_{city}}{GDP} = \frac{CE_{solid\ waste}}{Q_{solid\ waste}} \times \frac{Q_{solid\ waste}}{Pop_{city}} \times \frac{Pop_{city}}{GDP} + \frac{CE_{waste\ water}}{Q_{waste\ water}} \times \frac{Q_{waste\ water}}{Pop_{city}} \times \frac{Pop_{city}}{GDP} = EF_{solid\ waste} \times I'_{solid\ waste} \div GDP_{per\ capita} + EF_{waste\ water} \times I'_{waste\ water} \div GDP_{per\ capita} \quad (7)$$

where, CE_{waste} is total carbon emissions from waste disposal; GDP is gross domestic product in one year; $CE_{solid\ waste}$ and $CE_{waste\ water}$ make up the total carbon emissions from the waste disposal sector; Pop_{city} is the population of the city. $Q_{solid\ waste}$ and $Q_{waste\ water}$ are the quantity of solid waste and waste water production. $EF_{solid\ waste}$ and $EF_{waste\ water}$ are the emission factors for solid waste and waste water. $I'_{solid\ waste}$ and $I'_{waste\ water}$ represent the waste generation intensity per person.

In Eq. (7), the emission factor is determined by the solid waste disposal structure. For example, if we only consider two disposal modes, landfill and incineration, the emission factor can be further decomposed as:

$$EF_{solid\ waste} = \frac{CE_{solid\ waste}}{Q_{solid\ waste}} = \frac{CE_{landfill} + CE_{incineration}}{Q_{solid\ waste}} = \frac{CE_{landfill}}{Q_{solid\ waste}} + \frac{Q_{solid\ waste}}{Q_{solid\ waste}} = \frac{CE_{landfill}}{Q_{landfill}} \times \frac{Q_{landfill}}{Q_{solid\ waste}} + \frac{CE_{incineration}}{Q_{incineration}} \times \frac{Q_{incineration}}{Q_{solid\ waste}} = EF_{landfill} \times P_{landfill} + EF_{incineration} \times P_{incineration} \quad (8)$$

Constrained to:

$$P_{landfill} + P_{incineration} = 1 \quad (9)$$

In the above equations, $Q_{landfill}$ and $Q_{incineration}$ are the quantity of solid waste disposal by landfill and incineration; $EF_{landfill}$ and $EF_{incineration}$ are the emission factors for solid waste disposal by landfill and incineration; $P_{landfill}$ and $P_{incineration}$ are the proportion of landfill and incineration disposal.

2.3. Agriculture

Agriculture emissions include livestock and cropland emission, expressed as follows:

$$\frac{CE_{agriculture}}{GDP} = \frac{CE_{livestock} + CE_{crops}}{GDP} = \frac{CE_{livestock}}{GDP} + \frac{+CE_{crops}}{GDP} = \frac{CE_{livestock}}{A_{livestock}} \times \frac{A_{livestock}}{GDP} + \frac{CE_{crops}}{A_{crops}} \times \frac{A_{crops}}{GDP} = \frac{CE_{livestock}}{A_{livestock}} \times \frac{A_{livestock}}{Pop_{city}} \times \frac{Pop_{city}}{GDP} + \frac{CE_{crops}}{A_{crops}} \times \frac{A_{crops}}{Pop_{city}} \times \frac{Pop_{city}}{GDP} = EF_{livestock} \times I'_{livestock} \div GDP_{per\ capita} + EF_{crops} \times I'_{crops} \div GDP_{per\ capita} \quad (10)$$

where, $CE_{agriculture}$ is total carbon emissions from the agricultural sector; GDP is gross domestic product in one year; $CE_{livestock}$ and CE_{crops} make up the total carbon emissions from the agricultural sector; $A_{livestock}$ is the amount of livestock; A_{crops} is the area dedicated to agricultural crops. $EF_{livestock}$ and EF_{crops} are the emission factors for livestock and crops. $I'_{livestock}$ and I'_{crops} represent the livestock farming and crop cultivation intensity per person.

As for livestock, different livestock have different emissions (including enteric fermentation and manure management) per unit, so the amount of livestock $A_{livestock}$ is an equilibrium amount. It can be expressed by follows:

$$A_{livestock} = A_{cow} + \frac{CE_{per\ cow}}{GDP_{per\ pig}} \times A_{pig} + \cdots + \frac{CE_{per\ cow}}{CE_{per\ other}} \times A_{other} \quad (11)$$

where, A_{cow} and A_{pig} are cow and pig populations; $CE_{per\ cow}$ and $CE_{per\ pig}$ are the carbon emissions per cow and pig; other animals can be transferred to the cow equilibrium amount by $CE_{per\ other}$ and A_{other}.

For crop cultivation, we mainly consider the emissions from rice cultivation and fertilizer use in this paper as these are the two most important causal components in crop cultivation emissions. Other emissions from crop land can be decomposed according to the same principle.

$$EF_{crops} = \frac{CE_{crops}}{A_{crops}} = \frac{CE_{rice} + CE_{fertilizer}}{A_{crops}} = \frac{CE_{rice}}{A_{crops}} + \frac{CE_{fertilizer}}{A_{crops}} = \frac{CE_{rice}}{A_{rice}} \times \frac{A_{rice}}{A_{crops}} + \frac{CE_{fertilizer}}{Q_{fertilizer}} \times \frac{Q_{fertilizer}}{A_{crops}} = EF_{rice} \times P_{rice} + EF_{fertilizer} \times Q_{fertilizer\ per\ area} \quad (12)$$

where, CE_{rice} and $CE_{fertilizer}$ are the carbon emissions from rice cultivation and fertilizer use; A_{rice} is the area of rice cultivation; $Q_{fertilizer}$ is the quantity of fertilizer use; EF_{rice} is the emission factor for rice cultivation per area; P_{rice} is the proportion of rice cultivation to all crop land; $EF_{fertilizer}$ is the emission factor for fertilizer use per unit; $Q_{fertilizer\ per\ area}$ is the quantity of fertilizer use per area.

2.4. Industrial process

Process-related emissions include the mineral industry, chemical industry and metal industry. The mineral industry mainly includes cement, lime and glass production. The chemical industry and metal industry also have their sub-industries such as nitric acid, adipic acid and iron production.

$$\begin{aligned}\frac{CE_{industrial\,process}}{GDP} &= \frac{CE_{cement}+CE_{lime}+\cdots+CE_{other}}{GDP}\\ &= \frac{CE_{cement}}{Q_{cement}}\times\frac{Q_{cement}}{Pop_{city}}\times\frac{Pop_{city}}{GDP}+\frac{CE_{lime}}{Q_{lime}}\times\frac{Q_{lime}}{Pop_{city}}\\ &\quad\times\frac{Pop_{city}}{GDP}+\cdots+\frac{CE_{other}}{Q_{other}}\times\frac{Q_{other}}{Pop_{city}}\times\frac{Pop_{city}}{GDP}\\ &= EF_{cement}\times I'_{cement}\div GDP_{per\,capita}+EF_{lime}\\ &\quad\times I'_{lime}\div GDP_{per\,capita}+\cdots EF_{other}\\ &\quad\times I'_{other}\div GDP_{per\,capita}\end{aligned}\qquad(13)$$

where, $CE_{industrial\,process}$ is total carbon emissions from the agricultural sector; GDP is gross domestic product in one year; CE_{cement} and CE_{lime} are the carbon emissions from cement and lime production; Q_{cement} and Q_{lime} is the quantity of cement and lime production; EF_{cement} and EF_{lime} are the emission factors of cement and lime production; I'_{cement} and I'_{lime} represent the cement and lime production intensity per person. Other process-related emissions can be decomposed according to the same principle.

2.5. Forest

Forests act as carbon sinks and can be decomposed into different forest lands:

$$\begin{aligned}\frac{CE_{forest\,i}}{GDP} &= \sum_{i=1}^{n}\frac{CE_{forest\,i}}{GDP}=\sum_{i=1}^{n}\frac{CE_{forest\,i}}{A_{forest\,i}}\times\frac{A_{forest\,i}}{A_{forest}}\times\frac{A_{forest}}{Pop_{city}}\times\frac{Pop_{city}}{GDP}\\ &= \sum_{i=1}^{n}EF_{forest\,i}\times P_{forest\,i}\times I'_{forest\,i}\div GDP_{per\,capita}\end{aligned}\qquad(14)$$

where, CE_{forest} is total absorbed carbon emissions by forest; $CE_{forest\,i}$ is the amount of absorbed carbon emissions by i type forest land; A_{forest} is the area of total forest land; $A_{forest\,i}$ is i type forest land area; $EF_{forest\,i}$ is the absorption factor for i type forest land; $P_{forest\,i}$ is the proportion of i type forest land to all forest land; I'_{forest} represents the forest area per capita.

3. Target integrated low carbon city indicator system

3.1. Relationship between indicators and carbon intensity

Based on the above decomposed method, the indicators calculated by the decomposed method are drawn in Table 1. These indicators could offer a better approach for measuring performance of low carbon development and for taking action to reduce urban non-embodied carbon emissions. According to Eqs. (1)–(14), the aggregate GDP intensity of GHG emissions can be expressed as the function of the decomposed indicators, emission factors and other parameters:

$$I=\frac{CE_{total}}{GDP}=f(In_{decomposition}|EF\&Pa)\qquad(15)$$

$$\begin{aligned}In_{decomposition}\in\{&GDP_{per\,capita};P_{coal},P_{oil},P_{natural\,gas},P_{imported\,electricity};\\ &I_{primary\,industry},I_{secondary\,industry},I_{tertiary\,industry},I_{household};\\ &P_{primary\,industry},P_{secondary\,industry},P_{tertiary\,industry};I'_{solid\,waste},\\ &I'_{waste\,water};P_{landfill};I'_{livestock},I'_{crops};Q_{fertilizer\,per\,area};I'_{cement},I'_{lime};\\ &I'_{forest},P_{forest\,i}\}\end{aligned}\qquad(16)$$

$$\begin{aligned}EF\&Pa\in\{&EF_{coal},EF_{oil},EF_{natural\,gas},EF_{imported\,electricity};EF_{landfill},\\ &EF_{incineration};EF_{waste\,water};EF_{livestock};EF_{rice};EF_{fertilizer};EF_{cement},\\ &EF_{lime},EF_{other};EF_{forest\,i};P_{rice}\}\end{aligned}\qquad(17)$$

where, I is the aggregate carbon intensity of one year; *f() is the faction between carbon intensity and indicators, emission factors and parameters.* $In_{decomposition}$ is the indicator drawn by decomposed method; *EF&Pa* is the emission factors by different activities, and other parameters.

Table 1
Indicators calculated by decomposed method.

Activity	Related-indicators (from equations)
Energy use	Energy structure (2, 3, 4); industrial structure (2, 5, 6); sector energy intensity per unit of value added GDP (2, 5, 6); GDP per capita (2, 5)
Waste disposal	Solid waste disposal structure (7, 8, 9); solid waste generation per capita (7); wastewater generation per capita (7); GDP per capita (7)
Agriculture	Livestock farming structure (10, 11); agricultural cultivation structure (10, 12); livestock farming amount per capita (10); agricultural cultivation area per capita (10); fertilizer used per unit of agricultural land (10, 12); GDP per capita (10)
Industrial process	Process-related industry production per capita (13); GDP per capita (13)
Forest	Forest area per capita (14); Forest structure (14); GDP per capita (14)

3.2. Scenario analysis and indicator value

It is vital to calculate values for low carbon city indicator systems in the future as they provide a measurable, detailed and operational goal for municipal government administrators. In this study, the emission factors and some parameters in the decomposed formula are calibrated by historical data of emissions and activities. If the set of indicator values is assumed and determined according to scenario analysis, the carbon intensity of the value set can be estimated by the decomposed formula (as Eq. (15)). It is worth mentioning that the emission factors are often assumed to be constant, and this will affect the accuracy of carbon intensity calculation in some extent. By adjusting the indicator values by scenario analysis and comparing it with the baseline, the indicator values can be integrated to meet the national carbon reduction target. This will be further illustrated in the case study.

4. Case study

4.1. Study area and data use

Xiamen is a coastal city in southeastern Fujian province and is one of China's earliest Special Economic Zones. It lies at 118°04′04″ east longitude and 24°26′46″ north latitude, directly across from the Taiwan Strait. It covers an area of 1573 km^2 with a total population of 3.53 million in 2010 (XMBS, 2011). Xiamen's regional GDP reached 206 billion Yuan and the ratio of its 'three-industry structure'[1] is 1.1:49.7:49.2 in 2010. Xiamen's resident population

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[1] The 'three-industry structure' is the unit of measurement the Chinese government uses to track economic activity across various sectors. The three industries are primary industry, secondary industry and tertiary industry. Primary industry includes crop farming, forestry, livestock husbandry and fishery; secondary industry includes industry (including mining and quarrying, manufacturing, electricity, gas and water production and supply industry, etc.) and construction; tertiary industry includes other industries except the primary and secondary industry, mainly refers to service sector.

increased to 353 million in 2010, up from 225 million in 2005, with an average annual growth rate of 9.4%. In August 2010, Xiamen was identified as a low carbon pilot city as part of the NDRC's low carbon pilot project. This places a binding carbon reduction target on these pilot areas and Xiamen has set its city-level target in line with the national carbon intensity target. Xiamen is currently in the process of integrating its reduction target and additional low carbon performance requirements into its low carbon city planning strategy. An indicator system for meeting carbon intensity target is an important component of low carbon management for the municipal government.

Xiamen's forest carbon sink is only 0.24% of total carbon footprint in 2009 (Lin et al., 2013). This is very low and has little impact on the carbon reduction target. Xiamen also has very little of process-related industrial production within its city boundary, counting 0.35% of total carbon footprint in 2009 (Lin et al., 2013). Therefore, the forest-related and process-related indicators are omitted from the case study. The final low carbon city evaluation indicator set for Xiamen city is presented in Table 2, which focuses on non-embodied emissions by energy use, waste management and agriculture.

The energy emission factors of coal, refined oil and natural gas are from referenced from the Chinese Sustainable Energy Development and Carbon Emission Scenario Analysis (ERI, 2003). Part of Xiamen's electricity is imported from the Fujian State Grid and historical emission factors of the imported electricity are calculated based on energy structure data from the Chinese Energy Statistical Yearbook (2005–2010). 2.5 million kilowatts' wind power and 7 million kilowatts' nuclear power will be put into use by 2015 and 18 million kilowatts' nuclear power and more wind power will be put into use by 2020. Therefore the emission factors of the imported electricity will decline greatly in the future, see Appendix A. The historical emissions of waste and agriculture are calculated according to the 2006 IPCC inventory method and the related emission factors are calculated based on carbon emissions and activity data. Ignoring the impact of technological improvements and other factors, the future emission factors of waste and agriculture are drawn from historical data. The emission factors and parameters can be seen in Appendix A.

4.2. Results

The estimate value of the future per capita GDP and industrial structure ratio is provided by local government departments, as shown in Table 2. In this paper, two scenarios are studied, which are called general energy saving scenario (GES) and strengthened energy saving scenario (SES). In these two scenarios, the resident population will increase with annual growth rate of 9.07% and 8.88% in periods of 2010–2015 and 2015–2020, according to local planning. The difference between these two scenarios are the energy intensity and energy structure, other non-energy indicator values are the same. In the GES scenario, the energy intensity for 2015 will reduce 10% compared with a 2010 baseline level based on Xiamen City's Energy 12th FYP, and the reduction by 2020 compared with 2015 is also set to 10%. In the SES scenario, the energy intensity reduction for 2015 is 12% compared with a 2010 baseline level, and the reduction by 2020 compared with 2015 is also set to 12%. And the energy structure of GES scenario will be more optimized than SES scenario as shown in Fig. 1. Other non-energy indicator value indicators are primarily based on expert advice and government department interviews, in which the indicator values are further adjusted to satisfy the reduction by scenario analysis based on the decomposed method above. The carbon intensity reduction for 2015 and 2020 compared with 2005 is 35.45% and 45.53% in the GES scenario (Table 2), and they are almost the same in the SES scenario. The reduction contributions of different activities can be compute by Eq. (1) as shown in Fig. 2, in which Energy use contributes nearly 90% in average.

4.3. Discussion

Under the above two scenarios, energy intensity and energy structure are two primary drivers for carbon intensity reduction. And energy intensity is influenced by energy efficiency and economic structure (as Eq. (5)). The industry energy efficiency and economic structure are all improved under the two scenarios, shown in Table 2. But the household energy intensity will inevitably increase due to improvement of resident living standards, such as purchase and use of private cars, more household appliance uses,

Table 2
Final low-carbon indicators and values for Xiamen City.

Nos.	Indicator	Unit	Values of base year		Values by GES scenario		Values by SES scenario	
			2005	2010	2015	2020	2015	2020
1	GDP per capita[a]	10^4¥/person	4.4737	5.5167	6.6752	8.0103	6.6752	8.0103
2	Industrial structure[a]	%	2.1:54.9:43	1.1:49.7:49.2	0.5:47.5:52	0.1:40:59.9	0.5:47.5:52	0.1:40:59.9
3	Coal proportion in primary energy[b]	%	36.70	35.06	22.00	15.00	24.00	20.00
4	Refined-oil proportion in primary energy[b]	%	39.62	35.86	35.00	35.00	36.00	36.00
5	Natural gas proportion in primary energy[b]	%	0.00	7.28	18.00	25.00	18.00	21.00
6	Non-fossil proportion in primary energy[b]	%	0.00	3.77	5.00	6.00	4.50	5.00
7	Primary industry energy intensity[b]	tce[e]/10^4¥	0.4989	0.3981	0.3384	0.2910	0.3344	0.2876
8	Secondary industry energy intensity[b]	tce[e]/10^4¥	0.5874	0.5715	0.5315	0.4996	0.5201	0.4785
9	Tertiary industry energy intensity[b]	tce[e]/10^4¥	0.5267	0.3803	0.3118	0.2713	0.3004	0.2508
10	Household energy consumption per capita[b]	tce[e]/person	0.3963	0.5158	0.6395	0.7873	0.6395	0.7913
11	Per capita solid waste generation[c]	t/person	0.2704	0.2676	0.3077	0.3539	0.3077	0.3539
12	Solid waste landfill rate[c]	%	100.00	83.17	30.00	15.00	30.00	15.00
13	Per capita waste water generation[d]	t/person	76.46	69.02	65.57	62.29	65.57	62.29
14	Livestock farming amount per capita[a]	Num/10^4person	437	178	130	90	130	90
15	Agricultural cultivation area per capita[a]	mu[f]/person	0.3117	0.1253	0.0689	0.0482	0.0689	0.0482
16	Fertilizer used per agricultural land[a]	t/mu[f]	0.1405	0.1708	0.1571	0.1446	0.1571	0.1446
Carbon intensity reduction from 2005 level			**0.00%**	**17.76%**	**35.45%**	**45.53%**	**35.41%**	**45.53%**

[a] Data of 2005 and 2010 are from Yearbook of Xiamen Special Economic Zone.
[b] Data of 2005 and 2010 are from energy balance sheet by Xiamen Statistical Bureau.
[c] Data of 2005 and 2010 are from office of Xiamen city appearance, environment and sanitation.
[d] Data of 2005 and 2010 are from Xiamen Environmental Protection Bureau.
[e] tce is ton of coal equivalents.
[f] Mu is a common unit of land area in China, whereby 1 ha = 15 mu.

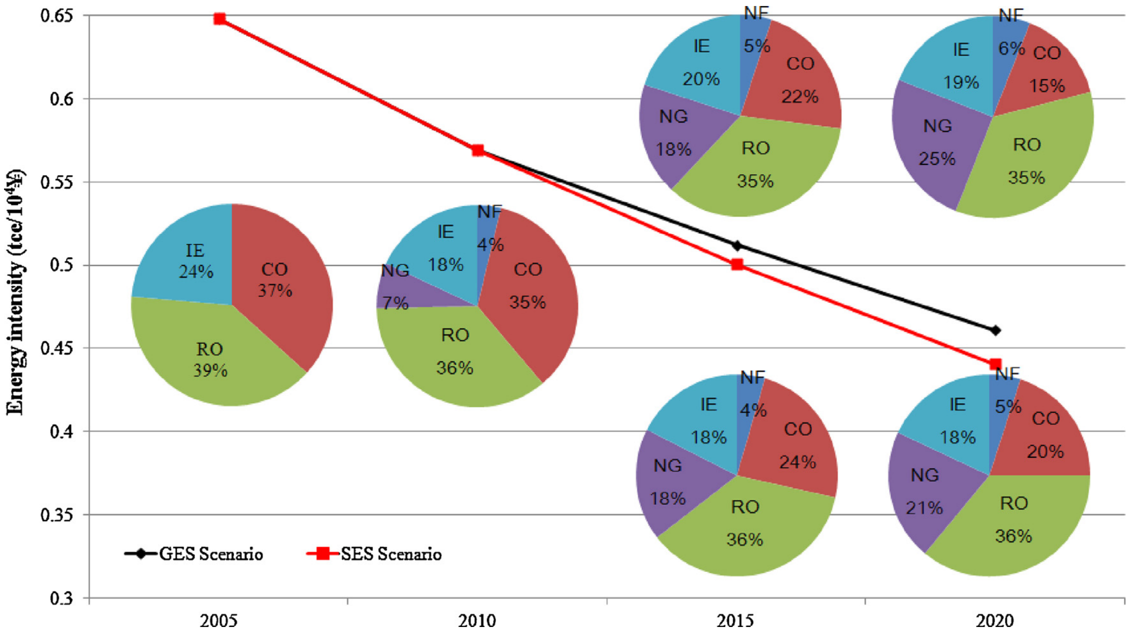

Fig. 1. Energy efficiency and structure of two scenarios. *Note*: CO, coal; RO, refined oil; NG, natural gas; IE, imported electricity; NF, non-fossil; above pie chart of 2015 and 2020 means GES scenario; and lower pie chart of 2015 and 2020 means SES scenario.

and etc. As for the energy structure, it is determined by fuel mix, which is optimized including power generation energy structure of imported electricity. The imported electricity comes from Fujian province Gird, in which nuclear power will play an important role in reducing carbon emissions (Wang et al., 2011). Nuclear power is life-cycle low carbon emission energy (Lenzen, 2008; Varun et al., 2009) in spite of its security-related and environmental challenges. The carbon intensity of waste will decrease due to transformation of waste disposal mode and efficient water use, even though per capita solid waste generation is increased in Table 4. The agricultural productions will decrease owning to urbanization, and these lead to further decline in carbon intensity of agriculture.

As mentioned above, the target discussed in this paper is carbon intensity just because the Chinese central government uses as assessment criteria. Intensity targets can address and reduce long-term cost uncertainty in some respects, but they does not guarantee that GHG emissions to the atmosphere will be reduced – absolute emissions may rise even if intensity goes down and output increases. Absolute targets are more transparent and environmentally robust as it entails a commitment to reduce GHGs by a specified amount, but they might be difficult to achieve under expected urbanization and industrialization in the next two decades in China. Currently, Chinese cities adopting binding carbon intensity targets as its international commitment would be a significant step toward committing to absolute emissions caps during the subsequent period. The emission scope of management is another topic, the increasing population and economic growth will lead to more embody emissions (Lin et al., 2013) which are now not included in government assessment criteria. In all, the future emphases of urban carbon management lie on transition to absolute target and wider managing scopes (Scope 3 emissions by WRI/WBCSD).

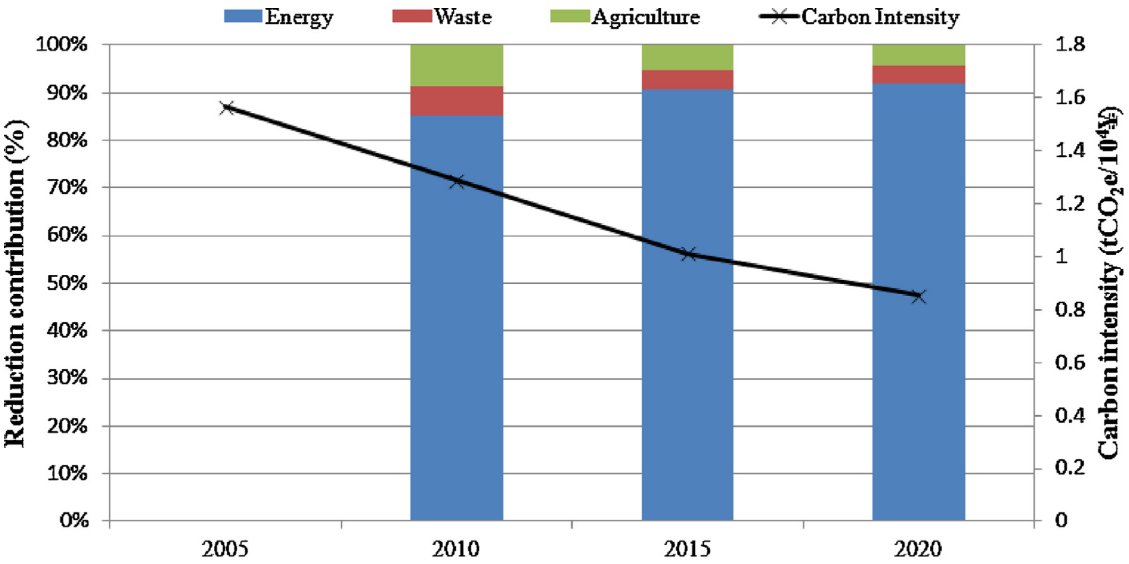

Fig. 2. Carbon intensity and its reduction contribution under two scenarios.

5. Conclusion

The pressure placed on provinces and cities through the imposition of binding carbon intensity targets has made it necessary to develop operational and target integrated low carbon city indicator systems to serve as a useful benchmark in assessing province- and city-level performance and provide information which is meaningful in designing local policy measures. In this research, we attempt to bridge the gap between carbon intensity reduction targets and low carbon city indicator systems by selecting indicators for the purposes of evaluating low carbon city development. This indicator framework goes beyond traditional approaches to low carbon performance evaluation in offering a more practical method for tracking low carbon city development and taking action to reduce urban carbon emissions.

In this paper, the target-integrated indicator system only presents a framework for estimating future carbon intensity and allows us to compare future performance against a base year. In order to develop more practical indicator values in the future, it will be necessary to carry out further sectoral surveys, cost-benefit analysis and repeated reduction target accounting, as well as including more consideration of embodied emissions. This will include carrying out a complete inventory calculation to get more accurate data on urban carbon emission intensity. To get more accurate carbon emission factors of activities, it needs a more accurate period historical inventory calculation. With more improvements, the target-integrated indicator system can provide more accurate information on quantitative and detail measurement for local governments to create low-carbon- or climate action plans.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.01.001.

References

Baeumler, A., Ijjasz-Vasquez, E., Mehndiratta, S., 2012. Sustainable Low-Carbon City Development in China. World Bank.

Chatham House, Chinese Academy of Social Sciences, Energy Research Institute, Jilin University, E3G, 2010. Low Carbon Development Roadmap for Jilin City.

China State Council, 2011. Working Plan to Control Greenhouse Gas Emissions in 12th FYP, Beijing (in Chinese).

ERI, 2003. Chinese Sustainable Energy Development and Carbon Emission Scenario Analysis. Energy Research Institute, National Development and Reform Commission, Beijing (in Chinese).

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

He, J., Yu, Z., Zhang, D., 2012. China's strategy for energy development and climate change mitigation. Energy Policy 51, 7–13.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havranek, M., Pataki, D., Phdungsilp, A., Ramaswami, A., Mendez, G.V., 2011. Greenhouse gas emissions from global cities (vol. 43, p. 7297, 2009). Environmental Science and Technology 45, 3816–3817.

Lenzen, M., 2008. Life cycle energy and greenhouse gas emissions of nuclear energy: a review. Energy Conversion and Management 49, 2178–2199.

Li, G., Wang, Z., Zhang, M., 2011. Research on the low-carbon economy evaluation model based on circulating revision – taking the low-carbon economic evaluation of Qinhuangdao as an example. Journal of Northeastern University (Natural Science) 32, 1790–1794.

Lin, J., Cao, B., Cui, S., Wang, W., Bai, X., 2010. Evaluating the effectiveness of urban energy conservation and GHG mitigation measures: the case of Xiamen City, China. Energy Policy 38, 5123–5132.

Lin, J., Liu, Y., Meng, F., Cui, S., Xu, L., 2013. Using hybrid method to evaluate carbon footprint of Xiamen City, China. Energy Policy 58, 220–227.

NDRC, 2010. Provincial Greenhouse Gas Emissions Inventory Guidelines, Beijing.

Price, L., Zhou, N., Fridley, D., Ohshita, S., Lu, H., Zheng, N., Fino-Chen, C., 2013. Development of a low-carbon indicator system for China. Habitat International 37, 4–21.

Song, L., Li, F., 2012. The assessment index system of low-carbon city development. In: 2011 International Conference on Energy, Environment and Sustainable Development, ICEESD 2011, October 21–23, 2011. Trans Tech Publications, Shanghai, China, pp. 1287–1294.

Varun, Bhat, I.K., Prakash, R., 2009. LCA of renewable energy for electricity generation systems – a review. Renewable and Sustainable Energy Reviews 13, 1067–1073.

Wang, R., Liu, W., Xiao, L., Liu, J., Kao, W., 2011. Path towards achieving of China's 2020 carbon emission reduction target – a discussion of low-carbon energy policies at province level. Energy Policy 39, 2740–2747.

WRI/WBCSD, 2004. The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard, revised ed. World Resources Institute/World Business Council for Sustainable Development.

XMBS, 2011. Yearbook of Xiamen Special Economic Zone, Xiamen Municipal Bureau of Statistics (XMBS) ed. China Statistics Press, Beijing (in Chinese).

Yan, W., Wang, Z., Han, G., Ye, L., 2011. Planning Indicators System and Implementation Approach for Low-Carbon Eco-City. Urban Planning Forum, pp. 39–50.

Yang, Y., Li, X., Zheng, H., 2011. In: Zhou, M. (Ed.), Analysis on Beijing's Low-Carbon City Evaluation Index System Education and Management, vol. 210. Springer, Berlin, Heidelberg, pp. 163–169.

Zhang, C.Q., Wang, Y., 2010. The Research of Evaluation Index System for Low-carbon City. IEEE, New York, pp. 270–273.