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Carbon Emission Efficiency of Construction Industry in Hunan Province and Measures of Carbon Emission Reduction

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ABSTRACT

The construction industry is among the pillars of China's economic development. However, it causes high carbon emission and high energy consumption, which should be considered when drafting energy saving and emission reduction policies. The sustainable development of this industry lies in the effective estimation of carbon emission efficiency and implementation of energy-saving and emission reduction measures in accordance with local practical situations. First, investigations on the emission efficiency of the construction industry and relevant emission reduction policies in foreign developed countries were reviewed in this study. Second, the carbon emission efficiency of the construction industry in 13 prefecture-level cities in Hunan Province (China) from 2011 to 2017 were estimated using the SBM (Slack Based Measure) model involving unexpected outputs. Finally, specific suggestions on reducing the carbon emission of the construction industry were proposed. CO_2 emissions in the construction industry increase annually as a response to economic development and urbanization. The carbon emission efficiency of Hunan Province's construction industry maintained a stable growth rate in 2011-2017. The industry achieved an annual growth rate of 2.7% in 2017 from that in 2011. The carbon emission efficiency of Changsha City, Zhangjiajie City, and Yiyang City were relatively higher than those of other cities in the province. Such findings serve as a reference to the quantification of potential of Hunan Province in reducing the carbon emission, the formulation of specific carbon emission reduction goal, the augmentation of the means to evaluate energy saving and emission reduction, and the development of a low-carbon construction industry.

INTRODUCTION

China's industrialization is currently progressing, and the resulting carbon emission has become a global concern. Recently, China's energy consumption increased remarkably as a result of the country's rapid economic development. The relationship among economic growth, energy consumption, and pollutant emission shows that the extensive development mode of high energy consumption and high pollution, single-energy structure, and the dominant roles of coal and petroleum are the main reasons why China tops the list in terms of CO_2 emission. China's construction industry is an important contributor to the national economy, but it involves energy consumption and carbon emissions. The influence of carbon emission on the construction industry affects the development of other industries. As a leader in the construction industry, China consumes more than half of its natural resources in construction activities, thereby generating abundant solid wastes. China is currently in the critical state of high-speed urbanization. The annual land development quantity increases with large-scale construction activities, which destroy not only the ecological environment, but also exacerbates the greenhouse effect. The consumption of natural resources for construction activities is among the main causes of climate warming. The current status of China's construction industry remarkably limits the goals to save energy and reduce emission.

Hunan Province is an important part of central China. The development trend of the construction industry and implementation of policy measures have resulted in region-wide progress. Fig. 1 presents the rapid development of the construction industry in Hunan Province, which is a traditional energy province in China. The total output of the construction industry increases every year. Considering the conflict between high carbon emissions caused by high energy consumption and the development goal of the construction industry, finding ways to effectively reduce energy consumption and carbon emissions while ensuring the industry's stable economic growth is an important research endeavour concerning the economic development and transformation of Hunan Province. Such an industry is an important pillar of Hunan Province's economy. It can absorb the material products of different industrial sectors and produce radiation and promotion effects to relevant industries due to its high industrial relevancy. As a result, carbon emissions related to construction industry is important for the Hunan Province's economic development. Carbon emissions of the construction industry come from two sources. First, the fossil energy consumed by production activities of the construction industry produces CO_2 emissions, including gasoline and diesel, which are needed for transportation. Second, carbon is also emitted during the industry's operations via heating and illumination. Therefore, analysing the carbon emission efficiency of Province's construction industry and proposing relevant emission reduction measures can provide a theoretical reference to the quantization of carbon emissions and guide the formulation of relevant policies.

PAST STUDIES

Carbon emission has attracted considerable attention from researchers worldwide due to the occurrence of global warming. Extant studies on the construction industry's carbon emissions mainly focused on accounting for carbon emission and its influencing factors, and they achieved substantial findings on the industry's current situation and carbon efficiency. Suzuki et al. estimated the energy consumption and CO_2 emissions in the entire life cycle of office buildings in Japan (Suzuki et al. 1998). Yan et al. believed that the manufacturing and transportation of construction materials as well as the installation and construction of buildings consume considerable energy sources and thus produce substantial greenhouse gases. He also carried out a case study on the greenhouse gas emissions of construction projects in Hong Kong (Yan et al. 2010). Acquaye et al. estimated the energy sources and carbon emissions caused by Ireland's construction industry by using the input-output method and analysed their influences on carbon emissions (Acquaye et al. 2010). Gustavsson et al. analysed the life cycle, primary energy utilization, and CO_2 emissions of an eight-floor wooden residential building; the result showed that the energy consumption for building operation accounted for the highest proportion of energy consumption in the entire life cycle (Gustavsson et al. 2010). Wu et al. believed that buildings are among the main factor of energy utilization and emission of greenhouse gases. Moreover, he also recognized and quantized the energy consumption of CO_2 emissions of the office building by using the LCA method (Wu et al. 2012). Wong et al. established that the construction industry has been a primary producer of greenhouse gases. A case study of an actual public house project proposed that possible carbon emission was simulated in the project planning stage and measured to reduce the carbon emissions of the building department as much as possible (Wong et al. 2013). Meng et al. argued that carbon transaction in the construction field promoted not only the energy-saving reconstruction of buildings and development of energy-saving technologies but also relieved financial pressure from the government. In addition, he proposed a framework for estimating carbon emissions in the construction industry (Meng et al. 2013). Jia et al. calculated the energy consumption and carbon emissions of the construction industry in Beijing from 1990 to 2012 and found that the energy consumption of the construction industry in 2012 increased by nearly four times in comparison with that in 1990 (Jia et al. 2014). Chuai et al. calculated the direct and indirect carbon emis-

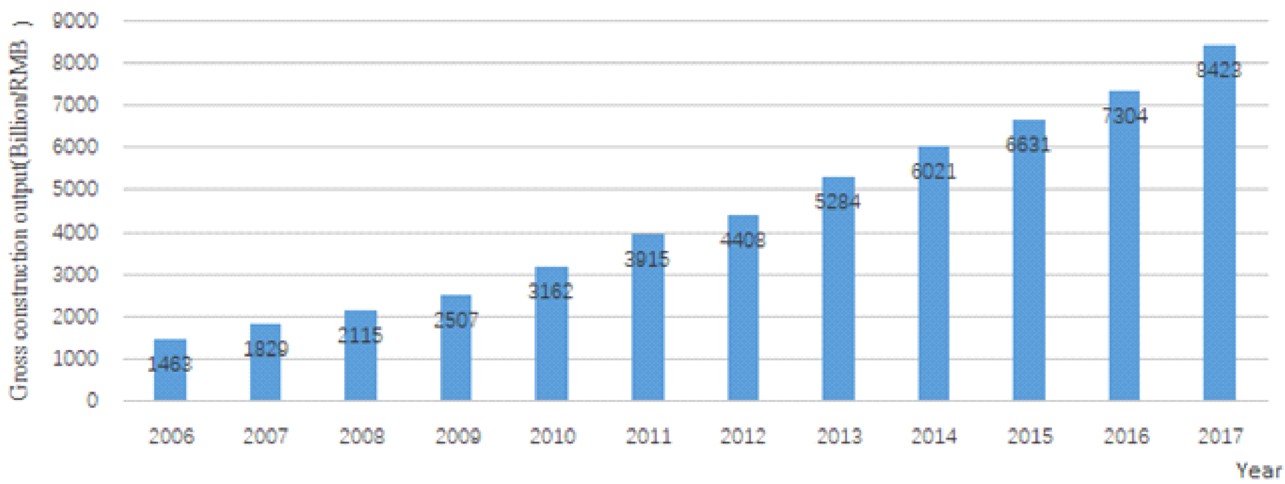

Fig.1: Total output of Hunan Province's Construction Industry in 2006-2017.
[Data source: China Statistical Yearbook (2018)]

sions produced by the energy consumption of China's construction industry in 1995-2010. He disclosed the significant regional differences in China with respect to carbon emissions of the construction industry. Southeast and the mid-southern regions of China were faced with strong pressure of carbon emission reduction of the construction industry (Chuai et al. 2015). Lu et al. evaluated the validity of carbon emission policies and calculated the carbon emission efficiency of buildings in China in 1994-2012. He found that the annual average growth rate of carbon emissions of China's construction industry was 6.9% in 1994-2012, and the "consumption of building materials" made the greatest contribution to the total growth of carbon emissions (Lu et al. 2016). Li et al. measured the total CO_2 emissions of the construction industry in Jiangsu Province in China and analysed the decoupling state between CO_2 emissions and economic growth in the construction industry (Li et al. 2017). Romanach et al. discussed the concepts of a household's comfort at home and energy efficiency as well as opinions of construction experts on low-carbon products and the housing market. Finally, they proposed measures for reducing carbon emissions of the construction industry (Romanach et al. 2017). Zhang et al. calculated carbon emissions on the basis of statistical data of the construction industry in China in 2004-2013; the results showed that the total emissions of the construction industry in China increased continuously and the carbon emissions during the construction activities was the highest (Zhang et al. 2017). Du et al. analysed the carbon emission characteristics of the construction industry in 30 Chinese provinces and regions and decomposed the main influencing factors by using the LMDI (Logarithmic Mean Divisia Index) model, including the proportion of direct energy source, energy consumption per unit value, value creation effect, indirect carbon intensity, and output scale effect. The results demonstrated that carbon emissions in most provinces increased from 2005 to 2014, whereas carbon emission intensity declined significantly (Du et al. 2018). Scholars have determined the correlation of the annual growth of CO_2 emissions of the construction industry with economic development and urbanization progress. However, the means of estimating carbon emission efficiency remains unclear. Foreign and local experts have replaced carbon emission efficiency from the single-factor perspective with carbon emission efficiency based on the total factors. Reducing the carbon emissions of the construction industry effectively relies on the accurate estimation of current carbon emission efficiency. In the current study, the SBM model involving unexpected output was applied to improve the estimation of carbon emission efficiency of the construction industry in Hunan Province and provide feasible suggestions for the formulation of energy-saving and emission reduction policies and the collection of quantitative information for policy analysis. The research conclusions provide theoretical references to realize low-carbon strategies of the construction industry in Hunan Province and promote the sustainable development of society.

BRIEF INTRODUCTION TO THE MODEL AND DATA PROCESSING

Superefficient SBM model involving unexpected output: The traditional DEA (Data Envelopment Analysis) method hypothesizes that all outputs are ideal but neglects the characteristics that certain practical output indexes can "reduce output and increase effects." Hence, this approach cannot evaluate the efficiency of unexpected output. To overcome the relevant defects of the DEA model, Tone proposed a non-radial and non-angled SBM model considering unexpected output (Tone 2001). In contrast to the BCC (Body center cubic) and CCR (A.Charnes & W.W.C Wooper & E. Rhodes) models, the SBM model directly adds the input-output slack variable into the objective function. This enhancement solves the input-output slack problem, evaluates the efficiency involving unexpected output, and avoids errors caused by the radial and angle selection. The input matrix is expressed as X: $X=(x_{ij})\in R^{m\times n}$. The expected output matrix is Y^g: $Y^g=(y^g_{rj})\in R^{s_1\times n}$. The unexpected output matrix is Y^b: $Y^b=(y^b_{tj})\in R^{s_2\times n}$. Moreover, $X, Y^g, Y^b \ge 0$; $1\le i\le m$; $1\le j\le n$; $1\le r\le s_1$; and $1\le t\le s_2$. j is the number of decision-making units, and i is the number of input element. S_1 and S_2 are the number of expected output and unexpected output factors, respectively. s_i^-, $s_r^{g^+}$, and $s_t^{b^+}$ are the slack variables of input, expected output, and unexpected output, respectively. The constant vector is $\lambda=(\lambda_j)\in R^{n\times 1}(\lambda\ge 0)$, which expresses the weights of j th decision-making unit. The superefficient SBM model involving unexpected output is expressed in Eqs. (1)-(2). The objective function is expressed as:

$$\rho^* = \min \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^{g^+}}{y_{r0}^g}+\sum_{t=1}^{s_2}\frac{s_t^{b^+}}{y_{r0}^g}\right)} \quad \text{...(1)}$$

The constraint is expressed as

$$s.t.\begin{cases} x_{i0} \ge \sum_{j=1,j\ne 0}^{n} x_{ij}\lambda_j - s_i^- \\ y_{r0}^g \le \sum_{j=1,j\ne 0}^{n} y_{rj}^g\lambda_j + s_r^{g^+} \\ y_{t0}^b \ge \sum_{j=1,j\ne 0}^{n} y_{tj}^b\lambda_j + s_t^{b^+} \\ 1-\frac{1}{s_1+s_1}\left(\sum_{r=1}^{s_1}\frac{s_r^{g^+}}{y_{r0}^g}+\sum_{t=1}^{s_2}\frac{s_t^{b^+}}{y_{r0}^g}\right) > 0 \\ \lambda, s^-, s^{g^+}, s^{b^+} \ge 0; 1\le i\le m; 1\le r\le s_1; 1\le t\le s_2; 1\le j\le n(j\ne 0) \end{cases} \quad \text{...(2)}$$

The final carbon emission efficiency of the construction industry (expressed in PE) can be expressed as:

$$PE = 1 + \frac{1}{s_2}\sum_{t=1}^{1}\frac{s_{t0}^{b^+}}{y_{t0}^{b}} \quad ...(3)$$

Data processing: According to the principle of selection, the production characteristics of the construction industry and model requirements, the construction industries of the 13 prefecture-level cities in Hunan Province were used as decision-making units (DMU) in the study period of 2011-2017. Input indexes were selected from the capitals, labour force, and resources. Fixed assets of the construction enterprise, number of employees of construction enterprises, and energy consumption were chosen as the input factors. The index measuring the economic output of the construction industry, that is, the added value of the regional construction industry, was used as the expected output. With consideration for the influences of carbon emissions on efficiency, CO_2 emission was chosen as the unexpected output. Specifically, the fixed assets of construction enterprises, number of employees of construction enterprises, and the total historical consumption of the construction industry were used as the capital input, labour force input of this empirical study, and energy input, respectively. The added value of the construction industry was used as the expected output and total carbon emissions (converted to standard coal) of the construction industry and applied as the unexpected output. The total carbon emissions of the construction industry were converted according to China's National Standard General Rule for Comprehensive Energy Consumption Calculation (GB/T 2589-2008). The remaining statistical data were collected from the Statistical Yearbook of Hunan Province of previous years.

RESULT ANALYSIS

According to Eqs. (1)-(3), the carbon emission efficiency of the construction industry in 13 prefecture-level cities of Hunan Province in 2011-2017 was calculated using the DEA-Solver software. The means of carbon emission efficiency of different regions were also calculated. Table 1 lists the results. Table 1 presents the following information:

1. The overall carbon emission efficiency of the construction industry in Hunan Province increased at a stable rate in 2011-2017. The carbon emission efficiency of the construction industry reached the highest (1.031) in 2017, which indicates an annual growth of 2.7% compared with that in 2011. This finding fully demonstrated that the construction area increased annually with the economic development of Hunan Province despite increase in the annual output of the construction industry. However, the carbon emission efficiency of the construction industry increased, leading to the gradual growth of resource utilization. This improvement might be related to the efforts of the provincial government of Hunan in restructuring the traditional construction industry since 2011. Such restructuring mainly includes the adjustment of labour force transformation, transaction of capital elements, market shares of foreign-funded markets, and market shares of state-owned enterprises. During the market structure adjustment, the relevant departments shall issue a series of policies and measures to promote the complete circulation of production elements (e.g., human resources) in market competition. Moreover, foreign-funded enterprises must be motivated into the market, making standard market behaviour condu-

Table 1: Carbon Emission Efficiencies of the Construction Industries in 13 Prefecture-level Cities in Hunan Province in 2011-2017.

	2011	2012	2013	2014	2015	2016	2017	Annual average
Changsha City	1.003	0.970	1.342	1.008	1.333	0.924	1.060	1.091
Zhuzhou City	0.753	1.159	1.055	0.874	0.675	0.985	0.805	0.901
Xiangtan City	1.185	0.848	1.025	0.632	1.130	0.706	0.996	0.932
Hengyang City	0.741	0.808	0.736	0.894	1.306	0.622	0.971	0.868
Shaoyang City	1.163	0.524	0.813	1.147	1.011	0.862	1.201	0.960
Yueyang City	1.059	0.940	0.684	0.819	0.896	1.246	0.881	0.932
Changde City	0.517	0.747	0.803	0.987	1.265	1.313	0.917	0.936
Zhangjiajie City	0.803	1.109	1.261	1.398	0.983	1.380	0.915	1.121
Yiyang City	0.784	1.350	1.300	1.015	1.036	0.972	1.337	1.113
Loudi City	0.874	1.034	0.548	0.874	1.086	0.874	0.954	0.892
Chenzhou City	0.801	0.673	1.246	1.036	0.697	1.220	0.940	0.945
Yongzhou City	0.987	1.095	0.710	0.566	0.865	0.834	1.222	0.897
Huaihua City	0.874	0.995	0.909	1.297	0.874	0.965	1.002	0.988
Tujia–Miao Autonomous Prefecture of Xiangxi	0.897	0.914	0.817	0.780	0.538	1.124	1.239	0.901
Mean	0.889	0.940	0.946	0.952	0.978	1.002	1.031	0.963

cive to promoting technological progress and injecting vitality into the construction market. In addition, the provincial government of Hunan advocates the use of energy-saving technologies and abandonment of products and technologies with high-energy consumption and high pollution to address backward technologies, low management level, and serious energy waste in the construction industry. For example, external wall insulation technology, peripheral shading technique, and heating technology with clean energy have been promoted to reduce carbon emissions of the construction industry. Environmentally friendly materials, such as recyclable and degradable matter, are applied to reduce energy consumption.

2. Changsha City, Zhangjiajie City, and Yiyang City have high carbon emission efficiency in Hunan Province's the construction industry. The tourism industry in Zhangjiajie City and Yiyang City has developed rapidly. The high-carbon emission efficiency of these two cities is related to the few construction activities, low input, and high input. Changsha City, which has the highest carbon emission efficiency, shows the highest economic development in Hunan Province. Although Changsha City is the provincial capital and has a very large construction area, many high-technology construction enterprises are located in this city. These enterprises increase energy utilization efficiency by increasing the technological R&D investment, training talents with management skills and professional technologies, strengthening R&D of energy-saving technologies, and enhancing the recycling of construction wastes, thereby improving the carbon emission efficiency of the construction industry in Changsha City.

CARBON EMISSION REDUCTION MEASURES OF THE CONSTRUCTION INDUSTRY IN HUNAN PROVINCE

Perfect policy system of construction technologies: Strengthening the functions of government in planning, coordination, and guidance is suggested. While implementing the national policy of energy savings and emission reduction, the government shall organize an expert committee on energy savings and emission reduction, explore to set up a carbon financial advisor center, and optimize the financial and technological information and demands of relevant enterprises. The government should enforce the orientation of market demand and perfect market mechanism and promote energy savings and emission reduction in the construction industry. The responsibility and supervision shall be determined clearly to prevent the overlapping of responsibilities. Moreover, support of the incentive measures of energy savings and emission reduction in the construction industry shall be perfected. Many market incentives are adopted to improve the enthusiasm of emission reduction in the construction industry. Policy supports, including accelerated depreciation, soft loan, and reduction or remittance of taxes, are implemented to new energy-saving buildings and high-efficiency construction equipment. Relevant fiscal subsidies shall be increased.

Perfect the standard system of green buildings: Green buildings are a systematic project that must timely follow the relevant standards and codes to achieve industrial development. The scoring standards of green buildings shall be unified and refined. The operable scoring standards, which cover practical environment and structure of buildings, shall be formed to improve the adverse environmental impacts of buildings and energy-saving efficiency and reduce cost. Construction greening shall be promoted. The government and its competent departments shall encourage the different regions to release local laws and regulations that enlist green construction and green buildings into the normative system. The promotion of green buildings shall be protected by institutions. Practical and effective management mechanisms shall be formulated and a management system shall be established under the guidance of the government. Multiple driving modes of green construction will be set up to realize the coordination and supervision of different departments in the industry, thereby developing the green construction industries.

Develop the modernization of construction industry: The construction industry has agreed to promote modernization. Building components, which are prefabricated in factories and assembled on-site, and Internet technologies are promoted in factories to accelerate updates in construction and increase the development quality of the construction industry. Determining the reasonable target tasks and development paths of modernization of the construction industry and promoting the modernized development of the construction industry will likely accelerate the transformation and upgrade of this industry. According to the short- and long-term development goals, a modernized production system, a market supervision system, a standard technical system, and a monitoring evaluation system of the construction industry shall be set up. In addition, the construction industry shall realize the interactive development of assembled buildings, finished houses, and green buildings; set up and supervise the standards and procedures of construction modernization; formulate detailed industrial policies; and perfect the standard system. The industrial policies shall cover the structure, layout, organization, technology, financial tax, and talent of the industry.

Promote energy-saving and technological development

of buildings: The energy-saving technological content of buildings increases continuously by combining government guidance and market promotion to realize the industrial development of energy-saving buildings and promote new energy-saving technologies and products. Such industrial alliance can help enterprises gain new technologies and expand market shares. Construction activities shall be planned and designed by increasing technological input and combining scientific technologies, economic efficiency, and social benefits. Hence, sufficient safe and clean resource and energy supply and emission reduction are the basic guarantee of economic development and social progress. It shall maintain low-carbon and energy-saving development of the construction industry, accelerate research on and use renewable and green energy sources, promote suitable innovative technology on energy savings and emission reduction, and facilitate the development of energy- and land-saving stereoscopic buildings.

CONCLUSIONS

The extensive development mode of the construction industry in China has led to the continuous increase of CO_2 emissions due to its high-energy consumption and high pollution. As an important source of national economic growth, the construction industry is the focus of energy consumption and carbon emission studies. The scientific evaluation of carbon emission efficiency of the construction industry in different regions, formulation of emission reduction measures according to local situations, and guidance of low-carbon green development of the construction industry have important academic values and practical significance. In this study, the carbon emission efficiency of the construction industry in 13 prefecture-level cities of Hunan Province in 2011-2017 were estimated by using the SBM model involving unexpected output, and specific measures to reduce carbon emissions were proposed. The research results showed that CO_2 emissions of the construction industry have increased annually due to economic development and urbanization progress. The carbon emission efficiency of construction industry in Hunan Province increased stably in 2011-2017. The carbon emission efficiency of the construction industry in 2017 achieved an annual growth rate of 2.7% compared with that in 2011. The carbon emission efficiency of the construction industry in Changsha City, Zhangjiajie City, and Yiyang City are relatively higher than the other cities. Apart from enriching the input-output indexes of carbon emission efficiency of the construction industry in the future, investigating the influencing factors of carbon emission efficiency, similarities and differences between China and other countries in carbon emission, division of responsibility of carbon emission reduction, and influences of carbon emission on environment have been suggested.

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