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Analyzing and optimizing the impact of economic restructuring on Shanghai's carbon emissions using STIRPAT and NSGA-II

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ABSTRACT

The economic restructuring of cities has a significant impact on their carbon emissions and is an important pathway to low-carbon development. China is the world's largest carbon emitter, but few studies provide an in-depth analysis of how economic restructuring is affecting carbon emissions at its city level. This study develops a Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model to analyze the impact of economic restructuring on CO_2 emissions in Shanghai. The results suggest that Shanghai's emissions have remained stable post-2007, largely due to the city's economic restructuring in favor of the tertiary sector: every 1% increase in the tertiary sector's share of GDP is associated with a 0.76% reduction in CO_2 emissions. This study also uses a multi-objective genetic algorithm, specifically the Non-dominated Sorting Genetic Algorithm II (NSGA-II), to optimize economic restructuring of Shanghai with regard to economic and climate objectives. The result suggests that Shanghai should aim to reduce the industrial share of gross output from 49.4% in 2012 to 38.3% in 2020. The main conclusion of the study is that Shanghai and, by extension, other Chinese cities, cannot achieve their climate targets without making meaningful changes to the economy geared towards less carbon-intensive activities.

1. Introduction

Cities are centers of anthropogenic activities, making them main contributors of greenhouse gas emissions (Satterthwaite, 2010). Cities thus play a critical role in mitigating climate change through the deployment of low-carbon strategies (Broto, 2017; Bulkeley, 2013; Lee & Painter, 2015; Lo, 2014c; Tsolakis & Anthopoulos, 2015; Zhou et al., 2015). Cities are also in perpetual flux, shifting economic priorities and configurations between sectors in Schumpeter's waves of creative destruction (Boschma, 2015; Tan, Zhang, Lo, Li, & Liu, 2017). As different sectors have different levels of energy consumption and CO_2 emissions, economic restructuring may lead to significant change to cities' overall carbon emissions (Schäfer, 2005). For example, in many high-income countries, the shift from an energy-intensive manufacturing economy to a service-oriented economy exerts a downward pressure on CO_2 emissions, whereas developing countries are becoming the main emitters of greenhouse gases as their economy moves towards energy-intensive heavy industries (Andreoni & Galmarini, 2016; Atalla & Bean, 2017). The Environmental Kuznets Curve (EKC) can be adapted to describe this inverted U-shaped relationship between economic development and carbon emissions (Kaika & Zervas, 2013; Khan, Zaman, & Zhang, 2016; Tang & Tan, 2015).

Since 1978, China has experienced an unprecedented rate of economic development and industrialization to become the world's largest manufacturing nation (Wei, 2017). China's level of industrialization, measured by industrial value added as a percentage of GDP, increased from 36.1% in 1990 to 41.3% in 2011 (Xu & Lin, 2015). The relationship between economic restructuring and carbon emissions has increasingly gained attention in China, following the government's pledge to peak carbon emissions by 2030 under the Paris Agreement (Mao et al., 2013; Sanwal & Zheng, 2016). Such an ambitious target demonstrates China's commitment to climate protection, but also presents new challenges in terms of how to achieve this target.

While the importance of renewable energy and energy efficiency in CO_2 mitigation is well established in the literature (Lo, 2014b; Lo & Wang, 2013), the role of economic restructuring is more ambiguous and is under-researched, especially at the city level. Several Chinese studies have examined the role of economic restructuring in energy consumption or emissions through decomposition analysis, but with inconclusive results. Some studies have found that economic restructuring has contributed significantly to a rapid rise in energy consumption and carbon emissions in China (Qi, Winchester, Karplus, & Zhang, 2014;

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Nomenclature

A	Affluence
c_i	Carbon emissions coefficient of sector i
CI_t	Carbon intensity in year t
E	Energy intensity (energy consumption per unit of GDP)
e_i	Error term of the STIRPAT model
EKC	Environmental Kuznets Curve
F	Final demand matrix
FDI	Foreign direct investment
GDP_t	Gross domestic product in year t
I	Impact
I_t	CO_2 emissions in year t
IC	Matrix of import coefficients
LMDI	Logarithmic Mean Divisia Index
M	Government spending in environmental protection
Max	Maximization function
Min	Minimization function
NSGA-II	Non-dominated Sorting Genetic Algorithm II
P	Population
STIRPAT	Stochastic Impacts by Regression on Population, Affluence and Technology
S^1	Percentage of the primary sector in GDP
S^2	Percentage of the secondary sector in GDP
S^3	Percentage of the tertiary sector in GDP
T	Technology
TC	Matrix of technical coefficients
TCE	Tons of coal equivalent
UM	Unit matrix
v_i	Industrial added value coefficient for sector i
X	Sector output vector
x_i	Economic output of sector i
θ	Weighting variable

Tang, Jin, Wang, Wang, & McLellan, 2017). However, other studies have found that economic restructuring may have a negative impact on carbon emissions. Tang, Jin, McLellan, Wang, and Li (2018) used the Logarithmic Mean Divisia Index (LMDI) method to identify economic restructuring as a key reason behind the recent slowing down of coal consumption in China. Li and Wei (2015) found that the impact of economic structure on China's CO_2 emissions has changed from positive to negative in recent years. Other studies have found the impact of economic restructuring on emissions to be relatively small or insignificant (Huang & Wang, 2016; Xu, Fan, & Yu, 2014; Yan & Fang, 2015; Yu & Kong, 2017). These differing conclusions may be related to discrepancies in the studied periods of time, methods, and the dependent variables (e.g., CO_2 emissions vs. energy consumption).

A common problem with these national-level analyses, however, is that they mask significant regional disparities in China. China is a very large and diverse country, where some cities have already entered into a phase of deindustrialization while others are still rapidly industrializing (Koo, Hayashi, Weng, & Bi, 2016; Li, Lo, & Wang, 2015; Li, Mu, Zhang, & Gui, 2012). Furthermore, given the increasingly decentralized nature of energy governance in China, a local analysis may be more useful from a policy perspective (Lo, 2014a, 2015). Due to these reasons, a number of regional- and city-level analyses have emerged recently, and they too have reached different conclusions. Wang, Wu, Zhu, and Wei (2013) used an extended STIRPAT model to study energy-related CO_2 emissions in Guangdong province and found that economic restructuring has a positive influence on CO_2 emissions. Wang, Zhao, Li, Liu, and Liang (2013) conducted an input-output structural decomposition analysis and revealed that economic restructuring is also driving an increase in CO_2 emissions in Beijing. Li, Lo, Wang, Zhang, and Xue (2016) found that industrial restructuring in northeast China has a negative impact on energy consumption. Wang et al. (2017) used STIRPAT to uncover that economic restructuring has little impact on CO_2 emissions in Xinjiang, northwest China. Li, Liu, and Li (2015) also found industrial restructuring to be the least important factor related to CO_2 emissions in Tianjin.

This paper presents the relationship between economic restructuring and carbon emissions in the context of Shanghai. As one of China's most developed cities, Shanghai plays a leadership role in both economic restructuring and low-carbon development (Yang, Wang, Lo, Wang, & Liu, 2015). It is one of the national low-carbon pilot cities and aims to achieve carbon peaking by 2020, which is ten years prior to the 2030 target for China (Khanna, Fridley, & Hong, 2014). The city has implemented one of the country's first carbon emission trading schemes, among other policy innovations (Liao, Zhu, & Shi, 2015; Wu, Qian, & Li, 2014). Therefore, the experience of decarbonization in Shanghai can provide important lessons for the rest of China, making it an appropriate choice for this study.

The methods and findings comprise a two-part study that examines the relationship between economic restructuring and carbon emissions in Shanghai. First, the authors extended the STIRPAT model to quantify the impact of economic restructuring on carbon emissions. This is to establish the importance of economic restructuring vis-à-vis other factors such as population, GDP, energy intensity, etc. Second, a multi-objective scenario analysis was conducted, which optimized economic restructuring for both economic and environmental objectives. This analysis is undertaken to determine which path of action would enable Shanghai to achieve low-carbon emissions and at what cost.

The results show that Shanghai cannot achieve its emission reduction targets without making structural changes to the economy geared towards less carbon-intensive activities. These results not only help to provide concrete policy suggestions on economic restructuring in Shanghai, but also have broader implications for other Chinese cities where many are aiming to achieve low-carbon status in the next decade.

The rest of the paper is structured as follows. The methodology and data collection are outlined in Section 2. Section 3 discusses Shanghai's recent economic and energy development, and levels of energy intensity and CO_2 emissions. The results are presented and discussed in Section 4. Section 5 highlights the theoretical and policy implications of the findings.

2. Methodology and data

2.1. Estimating CO_2 emissions and carbon intensity

The first step of the study is to calculate CO_2 emissions in Shanghai, both at the municipal level and at a more fine-grained sectoral level. This study follows the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), which outlines the calculation of CO_2 emissions from both stationary and mobile fossil-fuel combustion sources. Nine types of fuel that are commonly used in China were included in the calculation: coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, other petroleum products, and natural gas. Electricity was excluded to avoid double counting. Following the classification used in official statistical yearbooks, the study calculated CO_2 emissions from six sectors: (1) agriculture, forestry, animal husbandry and fishery; (2) industry; (3) construction; (4) transportation; (5) wholesale, retailing, and catering; and (6) other sectors.

Carbon intensity refers to CO_2 emissions per unit of GDP. An efficiency indicator, it reflects the level of low-carbon technological improvement. The equation to calculate carbon intensity is: