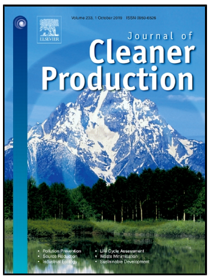

Measuring wellbeing performance of carbon emissions using hybrid measure and meta-frontier techniques: Empirical tests for G20 countries and implications for China

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Measuring wellbeing performance of carbon emissions using hybrid measure and meta-frontier techniques: Empirical tests for G20 countries and implications for China

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Abstract: A quantitative measure of performance that integrates national-level carbon emission profiles with key parameters of social and economic wellbeing can provide an effective management tool for policy interventions. This paper constructs non-parametric evaluation and decomposition models using hybrid measure and meta-frontier techniques. The proposed models are employed to estimate the wellbeing performance of carbon emissions (WPCE) and identify the sources of WPCE inefficiency. Empirical analyses based on the Group 20 (G20) countries for the 2000-2015 period shows the worst performance is in the BRICS country group (i.e. Brazil, Russia, India, China, and South Africa) – known for rapid growth – whereas the developed and the developing economies of the G20 group show positive trajectories of performance. As for China, its performance measure of WPCE was the lowest among the G20 indicating significant potential for further improvement. The analysis also highlights the role of managerial failure as the primary driver of inefficiency, more important than technological inefficiency in explaining efficiency loss within the G20 countries. This critical finding – the relevance and importance of managerial capability – suggests the need for a high level of attention to governance and managerial capacity to ensure continued improvements in performance on carbon emissions and human wellbeing. A lesson to be drawn from this study is that China's

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policies to promote a low carbon economy can benefit from increased priority given to low-carbon technological innovation for the energy system transition and enhancement of environmental governance and managerial capacity to achieve a long-term sustainability.

Key Words: Wellbeing performance of carbon emissions (WPCE); technical heterogeneity; undesirable hybrid DEA; meta-frontier analysis; Group 20 (G20).

1. Introduction

Climate change, caused by carbon dioxide emissions from fossil-fuel combustion, has become a dominant global concern in international political, economic and diplomatic discourse. With rapid growth of emissions from 9.40 billion tons in 1960 to 36.14 billion tons in 2014 (World Bank, 2018), the rising emissions are not only an existential threat for the health of bio-physical ecosystem, but will have profound consequences on human societies. Carbon emissions linked to climate change have been characterized as a "super wicked problem" with impacts on human welfare (Kerr, 2007; Levin et al., 2012) for many generations to come. The claim that climate change is primarily an environmental issue does not address the issue of economic growth patterns (Luo et al., 2017; Wang and Shao, 2019) and social wellbeing. Accordingly, the process of de-carbonization of an economy is actually a process of improving the carbon emission performance (Sonnenschein and Mundaca, 2016) in tandem with economic growth.

With dual challenges of a global climate crisis and the pressures of economic growth, the concepts of low-carbon development and green energy transformation is now widely recognized by the international community (Sterner and Damon, 2011). For example, with the establishment of carbon emission trading markets (Cong and Lo, 2017; Daskalakis, 2018; Weng and Xu, 2018) and carbon taxes (Farrell, 2017; Yu et al., 2018) worldwide, decarbonization (in relative or absolute levels) has evolved from a simple environmental issue to a major focus of global diplomacy. The strategy for transition of an economy to a low-carbon development pathway has become an important bargaining chip for international trade negotiations, politics and public policies.

The G20 comprises the world's 20 largest economies and accounts for 95% of global coal consumption, more than 70% of global oil and gas usage, 80% of global greenhouse gas emissions, and 85% of global investment in renewables (IRENA, 2017; Sikder et al., 2019). With its capacity to influence the direction of global change, and potential significant impacts on the global economy and environmental governance, the G20 needs to unify and take leadership to promote low-carbon and green transitions (Ram et al., 2018; Goldthau, 2017). To this end, in 2009 the G20 leaders committed to gradually end their countries' fossil fuel subsidies (Yao et al., 2015; Shao et al., 2017). Then, in 2012 at the Mexico Summit, the leaders stated that green growth policies were a priority and made a commitment to include green growth policies on the agenda at subsequent meetings (Bilgili and Ulucak, 2018). At the Saint Petersburg Summit in 2013, the G20 leaders again confirmed their commitment to address climate change and as well as pursuing economic growth strategies. Under Turkey's presidency in 2015, the G20 identified the Sustainable Development Goals (SDGs) as a core priority of the group. At the Hangzhou Summit in 2016, the G20 made a special statement on climate change, clearly expressing its active support for the Paris Agreement. Individual member countries also response to the initiative positively.

For example, the United States committed to reduce GHG emissions by 26–28% below 2005 levels in 2025; Australia committed to a 26–28% reduction of GHG emissions by 2030 below 2005 levels, including LULUCF; Brazil put forward an absolute emissions target of 1.3 GtCO2e/year by 2025 and an indicative target of 1.2 GtCO2e/year by 2030; Indonesia's NDC included an unconditional target of 29% below BAU and a conditional 41% reduction below BAU with sufficient international support by 2030, both including LULUCF; and Mexico in its NDC aimed to reduce its GHG emissions by between 22% (unconditional) and 36% (conditional) from BAU by 2030 (den Elzen et al., 2016; 2019). China promised to reduce carbon intensity by 40-50% by 2020 and 60-65% by 2030 (from its 2005 levels) with emission reduction targets assigned to 30 different provinces and municipalities (Tan et al., 2011; Chen and Yang, 2015; Chen et al., 2019).

Compared to other member nations, a low-carbon transition makes more sense for China as the country is currently the largest emerging market, energy consumer, and carbon dioxide emitter worldwide (Fu et al., 2015). It is also unique: given the country's fast economic growth together with a low-level of investment in low-carbon technologies, its social welfare has suffered primarily from ecological deterioration caused by rapid growth carbon emissions and other pollutants (Li and Zhou, 2016). Consequently, the country has committed to pursue low-carbon and inclusive growth by meeting Nationally Determined Contributions (NDCs). In September 2016, China officially joined the Paris Agreement, becoming the 23rd party to sign. The national focus is on accelerating the transformation of the economy to achieve the ultimate goal of improving the social welfare of all citizens through an economic system that promotes green development.

In this context, the development of a low-carbon economy through the improvement of carbon emission performance with welfare promotion is seen as a key path to achieve green growth and low-carbon transformation (Wang et al., 2014; Shao et al., 2019). In this study, we comprehensively evaluate carbon emission performance from the perspective of wellbeing for all the world's leading countries, examine the upside potential in the international arena, identify the causes and reasons for performance loss and point to the path for improvement, especially for a unique country like China. With this background, this study constructs a non-parameter model to estimate the performance impacts of carbon emissions on wellbeing (WPCE) of the G20 countries. The next step is a decomposition analysis to reveal underlying factors that account for inefficiency of divergent economies. This allows us to draw China-specific suggestions for improvements and recommendations that emerge from an international comparison with the G20 group of countries. The quantitative recommendations are intended to facilitate inclusive growth of the biggest emerging and developing country in the world.

The rest of the article is organized in the following way: section 2 reviews the literature on the evaluation of carbon emission performance and proposes the contributions of this study. Section 3 describes non-parametric evaluation and meta-frontier methods, and specifies the data sources of carbon emission performance analysis as well as input and output variables from 2000 to 2015. Section 4 empirically analyzes and discusses the carbon emission welfare performance for G20 countries. Section 5 discusses the findings and suggests policy implications.

2. Literature review and research contribution

Productivity and efficiency analysis of carbon emissions has become a main approach for estimating carbon emission performance. Moreover, such analysis is also considered an effective tool to combine the two major features of low-carbon economy: that is, to reduce carbon emissions while maintaining economic growth (Beinhocker et al., 2008).

2.1 Analytical perspective and framework of carbon emission performance.

Two major analytical perspectives inform the framework of carbon emission performance. The first perspective focuses on the economic aspect of carbon utilization, initially proposed by Kaya and Yokobori (2002). In this study, carbon productivity, also called carbon intensity, was measured by a ratio of economic outputs (i.e., GDP) per unit of CO_2 emissions. Later studies based on this economic perspective usually take carbon as an element embedded in energy and products to reflect the economic gains from carbon resources. Such economic-based analyses brought in a useful angle to evaluate and compare carbon emission performance, and have been widely applied and enriched in the carbon management realm (Yu et al., 2017).

After the 1980s, serious environmental, ecological, and societal issues introduced by climate change made emission mitigation a serious focus in order to maintain and enhance social welfare on different levels. Direct and indirect impacts of carbon dioxide emissions on the quality of environment and ecosystem pose immense obstacles in the path to sustainable development. Against this background, environmental, social, and wellbeing effects of carbon emissions started to be taken into account when measuring performance (Liu and Cao, 2011; Givens, 2015; McGee et al., 2017).

2.2 Analytical methods and techniques of carbon emission performance.

Two types of methods have been formed so far to estimate carbon emission performance on macro levels: single-factor approach and total-factor analysis. Single factor method usually takes the form of ratio, such as CO_2 emissions per unit of energy consumption (also called “carbonization index”), the reciprocal of carbon intensity (i.e., the ratio of GDP to CO_2 emission), CO_2 emission per capita, ratio between carbon emissions and life expectancy, and the ratio of Human Development Index per unit of CO_2 (Yi et al., 2011; Peng et al., 2015). Such a method is usually direct, simple, concise, and easy to apply (Goh et al., 2018). However, single factor analysis also has certain constraints: it doesn’t incorporate relevant and critical production factors nor does it reflect the substitutions of elements (Ramanathan, 2005). Along with the development of the research regarding the theme, total factor analysis has been adopted to measure carbon emission performance based on the production theory by taking into account labor, energy, and capital inputs (Zhou et al., 2010). Compared to single-factor indexes, such a method is considered more advanced and robust with its capability of incorporating multiple relevant inputs as well as various outputs introduced by carbon emissions.

Non-parametric and parametric techniques represented by Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) are commonly used to complete the empirical tests of carbon productivity estimation. Compared to SFA, the DEA approach is more flexible and applicable with its capability to deal with multiple input and output indicators. Moreover, a DEA model doesn’t require setting the forms of functions in advance (Yao et al., 2016). Accordingly, DEA-based techniques are widely used for total factor performance evaluation for carbon emissions. For example, Wang and Li (2018) unitized a DEA model to generate total factor carbon efficiency scores to reflect carbon emission performance of a set of independent oil and natural gas producers in the United States for the period 2011–2015. Iftikhar et al. (2016) employed the slack-based model of DEA to measure the CO_2 efficiency of 26 major economies in 2013 and 2014. Wang et al. (2016a) used an expended directional distance function model of DEA to observe carbon productivity changes of 37 major carbon emitting countries and regions from 1995–2009. Hu and Liu (2016) constructed a DEA based Malmquist index to evaluate carbon emission performance of the Australian construction industry from 1990 to 2013.

2.3 Cross-country comparison of carbon emission performance.

As an international focus, carbon emission performance comparison based on various economies has become a burgeoning topic in the field of climate policy research. Even though both single-factor and total-factor analysis are utilized in research studies, existing comparisons mainly focus on the economic perspective of carbon emission performance. In addition, research findings and conclusions of carbon emission performance vary greatly because of the divergences in research sample, method, and time window selected.

For example, Rodríguez and Pena-Boquete (2017) compared the carbon emission performance of 9 emerging East Asian countries based on the changes of carbon intensity index during 1990-2011. The results demonstrate that CI dropped greatly for China whereas increased slightly for Thailand, Malaysia, and Indonesia. Using the slacks-based measure (SBM) approach, Wang et al. (2017a) found a lower performance in Asia than in Europe and the Americas, yet the Asian countries had the greatest potential in performance improvement. Chang et al. (2017) studied dynamic trends of carbon intensity of 127 countries from 1980-2011. Their findings indicated a decreasing trend of carbon intensity in general, yet the decreasing rates for individual countries were divergent to a great extent and most middle- and low-income economies experienced a growing trend of CIs. Emir et al. (2019) observed the convergence situation of carbon intensity in EU-28 countries but found that inequity of the performance (i.e., carbon intensity) was significant across the member countries. Therefore, updated strategies should be designed and adopted to change such status and to meet the Europe Union environmental regulation standards. Zhang et al. (2018b) evaluated the carbon emission performance of a main Clean Development Mechanism (CDM) host and investment countries during the years 1990–2015. The results indicated that countries investing in CDM projects showed much higher emission performance than the hosts.

Along with the development of research in the field, technology heterogeneity across countries started to be taken into account to reveal determinants of performance loss (Wei et al., 2019). For example, Wang et al. (2016b) employed total factor analysis for 54 countries to evaluate carbon emission performance, and found that managerial inefficiency plays a more important role in reducing carbon emission performance compared to technical inefficiency in general. Comparatively, another study conducted by Wang et al. (2016a) revealed that technical progress played the most critical role in carbon productivity improvement of 37 major carbon emitting countries and regions from 1995–2009.

2.4 Research gaps and contributions of this study

The prior literature has provided us with valuable references and foundations regarding the topic of carbon emission performance evaluation. However, certain research gaps still exist and need to be fulfilled.

- One limitation of the collective body of knowledge and current research on carbon emission performance evaluation is that the studies mainly focus on economic or environmental performance of emissions. Robust analyses from the perspective of welfare evaluation, especially ones with total factor approach, are relatively rare (Slaughter, 2017; Paramati et al., 2017).
- Moreover, most studies utilize either radial or non-radial DEA models to evaluate carbon emission performance without considering the possible drawbacks of such approaches. In addition, despite the disparities of observations starting to be taken into account, consensus conclusions haven’t emerged from the literature.
- Additionally, to the best of our knowledge, a comprehensive study on carbon emission performance, that draws on a perspective of wellbeing for the G20 economies with a wide range in country levels and great representativeness is still lacking. In accordance, divergent paths for performance enhancement of economies with different background are still unclear.

Therefore, this study sets out to fill the aforementioned research gaps and aims to enrich the existing literature in the following aspects.

In terms of analytical framework, this study proposes a total factor analytical framework for carbon emission performance evaluation from the perspective of wellbeing (i.e., wellbeing performance of carbon emissions, WPCE). The proposed WPCE indicator is an attempt to enrich the prior research that either focuses merely on the economic perspective of emissions or relies on single factor analysis.

In terms of analytical method, an undesirable hybrid measure model based on DEA that deals with radial and non-radial issue simultaneously is constructed in this study to estimate the WPCE on a national level. A meta-frontier approach is further utilized and combined with the hybrid model to incorporate the heterogeneity across the research sample to reveal technical gaps across different types of economics (i.e., advanced countries, emerging markets represented by the BRICS, and other large developing countries). The proposed models can serve as useful tools for other similar studies.

In terms of analytical object, empirical tests based on the 20 large and diversified countries are conducted to present the levels and variations of WPCE. Moreover, this study also observes determinants of performance loss and reveal various paths to performance gains in countries with different backgrounds. Implications for China are further posited based on the comparative analysis of the 20 countries. Such research findings will contribute to enrich the discussion in environmental management fields.

3. Model specification and data collection

3.1 Model specification

Hybrid measure model was first proposed by Tone (2004) to simultaneously address drawbacks of radial and non-radial techniques in Data Envelopment Analysis (DEA). Drawing on the initial model by Tone and Tsutsui (2006), this study constructs a non-oriented hybrid model with undesirable variables (i.e., undesirable hybrid measure, UHM) by referencing the research of Lu et al. (2013). Suppose we have n Decision-Making Units (DMUs) in total and each DMU uses s inputs to generate m outputs. The inputs can be further divided into radial (s_1) and non-radial

(s_2) parts with $s=s_1+s_2$, and the outputs can be decomposed into radial good (m_1), radial bad (m_2), non-radial good (m_3), and non-radial bad parts((m_4) with $m=m_1+m_2+m_3+m_4$. Then the efficiency score of any given DMU$_0$ can be obtained by solving the following program:

$$\varepsilon = \min \frac{1-\frac{s_1}{s}(1-\theta)-\frac{1}{s}\sum_{i=1}^{s2}\frac{s_i^{NR-}}{x_{io}^{NR}}}{1+\frac{m1}{m}(\phi-1)+\frac{m2}{m}(\varphi-1)+\frac{1}{m}\sum_{r=1}^{m3}\frac{S_r^{NRg+}}{\mathrm{y}_{ro}^{NRg}}+\frac{1}{m}\sum_{j=1}^{m4}\frac{S_j^{NRb+}}{\mathrm{y}_{jo}^{NRb}}} \tag{1}$$

$$\text{s.t.}\ \begin{aligned}
&\theta x_o^R = X^R\lambda + s^{R-};\\
&x_o^{NR} = X^{NR}\lambda + s^{NR-};\\
&\phi y_o^{Rg} = Y^{Rg}\lambda - s^{Rg+};\\
&\varphi y_o^{Rb} = Y^{Rb}\lambda - s^{Rb+};\\
&y_o^{NRg} = Y^{NRg}\lambda - s^{NRg+};\\
&y_o^{NRb} = Y^{NRb}\lambda - s^{NRb+};\\
&\theta \le 1, \phi \ge 1, \lambda \ge 0, s \ge 0;\\
&s^{Rg+} \ge 0, s^{Rg-} \ge 0, s^{Rb+} \ge 0, s^{Rb-} \ge 0, s^{NR-} \ge 0;\\
&s^{NRg+} \ge 0, s^{NRg-} \ge 0, s^{NRb+} \ge 0, s^{NRb-} \ge 0.
\end{aligned} \tag{2}$$

where, ε is the efficiency score of a given *DMUo* under the hybrid model of equation (1) and λ represents the intensity vector. Specifically, θ, φ, and ϕ are radial parameters of the model while *S* is short for slacks, respectively. "*NRg*" and "*NRb*" are the abbreviations of "non-radial good (i.e., desirable)" and "non-radial bad (i.e., undesirable)", respectively. Metrics of inputs and outputs are denoted as $X \in R^{s\times n}$ and $Y \in R^{m\times n}$, respectively. In accordance, the radial part and non-radial part of the input matrix are expressed as $X^R \in R^{s1\times n}$ and $X^{NR} \in R^{s2\times n}$, respectively. Similarly, the expected radial part, unexpected radial part, expected non-radial part and unexpected non-radial part of the output matrix as $Y^{Rg} \in R^{m1\times n}$, $Y^{Rb} \in R^{m2\times n}$, $Y^{NRg} \in R^{m3\times n}$ and $Y^{NRb} \in R^{m4\times n}$, respectively. In accordance, the optimal solution of any given DMU$_0$ (i.e., ε) can be calculated using the equation (1) under the constraint conditions listed above with the help of MAXDEA, a professional software for DEA that has been widely used in academic research (Zheng et al., 2015; Cheng, 2014; Halkos and Petrou, 2019). The efficiency score estimated falls into the range of (0, 1] and a DMU is considered efficient when its score reaches 1.

However, one ground assumption of traditional DEA methods is that all DMUs are homogeneous and operate on the same production frontier. Such assertion is difficult to meet in the real world and easily leads to biased estimations as observations are usually made by researchers with various backgrounds and technical levels. The meta-frontier approach is subsequently proposed to address this problem and serves as a reliable perspective to observe technical differences across DMUs (O'Donnell et al., 2008). Such perspectives combined with DEA approaches have seen incremental development and are increasingly used in environmental-related discourse (Oh, 2010).

Considering the production technical heterogeneous attribute to divergent context-settings, observations can be categorized into several sub-groups to form two different production frontiers, namely the meta-frontier and the group-frontier. In accordance, the production technology set of the *k*-th group under the group frontier and meta-frontier can be denoted as T^{meta} and T^k, respectively. For any k, if an input-output combination (a, b, c, d, e) belongs to T^k, then (a, b, c, d, d) belongs to T^{meta} as well. As such, $T^{meta} = \left\{T^1 \cup T^2 ... T^k\right\}$ meets the over-arching requirement, and the technological gap for a given DMU belongs to the *k*-th group can be obtained by comparing its efficiency values under the two frontiers.

Referencing the research of Chiu et al. (2012), this study categorizes the 20 countries into developed and developing groups based on the income standard of the World Bank (2018). In view of the BRICS countries' salient economic growth as well as their noteworthy contributions to the global energy consumption and carbon emissions over the years, these economies are then separated from the developing countries to form an independent set. As such, three sub-groups are formulated (i.e., *k=3*), namely, the developed group, the BRICS group, and the developing group without the BRICS (hereafter, the developing group).

Accordingly, the technology gap ratio (TGR) of the *n*-th country in the *k*-th group can be obtained using the following equation.

$$TGR_n^k = MCP_n \big/ GCP_n^k \tag{3}$$

where, MCP_n and GCP_n^k denote the efficiency value of the *n*-th country estimated based on a meta-frontier and a group frontier, respectively. Subsequently, MCP≤GCP always stands and TGR∈ (0 , 1]. A smaller score of TGR indicates a larger gap between the two frontiers, yet it also implies a greater potential in efficiency gains for assessed DMU. The total efficiency loss due to technology, represented by MTI (Meta Total Inefficiency), can be further decomposed into technological gap inefficiency (TGI) and managerial inefficiency (MI) with the help of the following equations.

$$MTI_n^k = TGI_n^k + MI_n^k = \rho_n^{meta} \tag{4}$$

$$TGI_n^k = GCP_n^k(1 - TGR_n^k) = \rho_n^{meta} - \rho_n^k \tag{5}$$

$$MI_n^k = 1 - GCP_n^k = \rho_n^k \tag{6}$$

Generally, technical gap inefficiency is usually originated from the technical heterogeneity across DMUs, i.e., the differences regarding the capacity to transfer inputs into more good outputs with less undesirable products. Such disparity can be narrowed down through balancing technical levels among countries to prompt technical progress and provoke latent capacities of backward countries/regions. Comparatively, managerial failure, also known as allocative inefficiency, is commonly attributed to a low-level of resource allocation and governance shortfalls in environmental regulation (Du et al., 2015; Feng and Huang, 2016). In addition, all abbreviations for the terms used in the study are displayed in **Table 1**.

Table 1. Full name and definition of abbreviations used in the study

Abbreviation	Full name	Definition
WPCE	welfare performance of carbon emissions	total factor efficiency of carbon emissions from the perspective of welfare
DMU	decision-making unit	samples (i.e., the 20 countries)
UHM	undesirable hybrid measure	hybrid model with undesirable variables
TGR	technology gap ratio	ratio of efficiency values estimated under the two frontiers
MCP	meta-frontier carbon emission performance	efficiency value of a DMU estimated based on a meta-frontier
GCP	group-frontier carbon emission performance	efficiency value of a DMU estimated based on a group-frontier
MTI	meta-frontier total inefficiency	total efficiency loss measured under a meta-frontier
TGI	technological gap inefficiency	efficiency loss caused by technology gap
MI	managerial inefficiency	efficiency loss caused by managerial failure

3.2 Indicators and Data

Since the beginning of the 21st century, the G20 has gradually replaced the original Group 8 (G8) as the dominant and primary mechanism of world governance. With its significant impacts on global economy, environment, and society, G20 advocates the widespread dissemination of a series of international norms concerning development (Huang, 2014), thus the group has strong representativeness and analytical value in this study. Input and output indicators are selected based on data availability by referring to the selection and treatment of proxy variables in related research (Zhang et al., 2015b). In addition, considering the statistical feasibility and representativeness of the research observations, Spain is used to replace the EU to form a complete sample of 20 countries. Data for G20 economies during 2000-2015 are collected for carbon emission performance analysis.

Output indicators include carbon dioxide emissions and welfare performance. (i)

Carbon dioxide emissions are determined as the radial undesired "bad" output of this study, with the total amount of carbon dioxide emissions of each country in international statistics as the proxy variable. Annual carbon emission data are collected from the statistical yearbook of British Petroleum (BP). (ⅱ) Welfare performance is determined as the non-radial desired output indicator in this study. Existing welfare indicators for international comparison mainly include the Human Development Index (HDI) and Life Expectancy (LE) as well as improved indicators based on GDP. Specifically, the improved indicators based on GDP include the Index of Sustainable Economic Welfare (ISEW) (Menegaki and Tugcu, 2018), the Genuine Progress Indicator (GPI) (Brown and Lazarus, 2018), and the Sustainable Net Benefit Index (SNBI) (Lawn and Sanders, 1999). Life expectancy is a comprehensive reflection of human wellbeing and welfare that comprises the material standard of living, physical condition, mental state, social atmosphere, ecological environment and even the political system (Verstraeten et al., 2016; d'Albis and Bonnet, 2018; Jiang et al., 2018; Hill and Jorgenson, 2018). In this study, life expectancy is used as the proxy variable of welfare performance.

In terms of input indicators, energy and non-energy are selected to reflect the consumption of labor, capital and natural resources. Specifically, (ⅰ) energy input, which is determined as a radial input indicator, and takes the total amount of national primary energy consumption as a proxy variable. Primary energy consumption is used to reflect the total energy consumption within a certain time range of the economy. The data is collected from the BP statistical yearbooks. (ⅱ) Labor input is determined as a non-radial input indicator, which is reflected by the number of employees in each country across the research period. Since there are no direct statistics on the number of people working, the total number of a country's labor force and the corresponding employment rate in the World Development Indicator (WDI) database are used for calculation (World Bank, 2018). (ⅲ) Capital input, which is determined as a non-radial input indicator. The perpetual inventory method is used to calculate the capital stock of each country by referring to Wei et al. (2011). To eliminate the impact of price fluctuations, the capital stock is converted to the fixed price of USD in 2010. Related data are obtained from the WDI database. Statistical distribution characteristics of the variables employed for the 20 countries during the observation period in this study are presented in **Table 2**.

Table 2. Summary for statistical distribution of variables (2000-2015).

Variables	**Mean**	**SD**	**Min**	**Max**	**Unit**	**Date source**
Labor force	97.25	175.26	6.39	767.88	Million	WDI (2018)
Capital stock	6,553.6	7,775.81	673.54	37,911.5	Million $	WDI (2018)
Energy consumption	441.30	623.45	58.34	3,005.95	Million metric tons	BP (2018)
Carbon emissions	1,163.46	1,829.22	118.53	9,224.10	Million metric tons	BP (2018)
Life expectancy	75.17	7.04	51.56	83.84	years	WDI (2018)

Note: SD denote standard deviation.

4. Empirical analyses and discussions

Drawing on the models constructed in Section 3, panel data for G20 countries from 2000 to 2015 are used for empirical tests. Combined with formulas (1), (2) and (3), MCP, GCP and TGR of G20 are calculated during the observation period. **Table 3** presents the average WPCE scores of MCP, GCP and TGR in 20 countries during the observation period (i.e., 2000-2015).

Table 3. Average scores of WPCE for G20 under the meta-frontier and group-frontier.

Country	*MCP*	*GCP*	*TGR*	*Country*	*MCP*	*GCP*	*TGR*
Australia	1.000	1.000	1.000	Argentina	1.000	1.000	1.000
Canada	0.409	0.601	0.679	Indonesia	0.261	0.261	1.000
Germany	0.195	0.286	0.682	Mexico	0.284	0.284	1.000
Spain	0.522	0.983	0.532	Saudi Arabia	1.000	1.000	1.000

France	0.344	0.650	0.534	Turkey	0.541	0.541	1.000
United Kingdom	0.293	0.471	0.621	**Developing countries**	0.617	0.617	1.000
Italy	0.386	0.624	0.618	Brazil	0.197	1.000	0.197
Japan	0.117	0.158	0.737	China	0.028	0.046	0.625
South Korea	0.345	0.587	0.588	India	0.088	0.165	0.540
United States	0.040	0.049	0.814	Russia Federation	0.110	0.199	0.551
Developed countries	0.365	0.541	0.681	South Africa	0.551	1.000	0.551
G20	0.392	0.547	0.725	**BRICS countries**	0.195	0.482	0.493

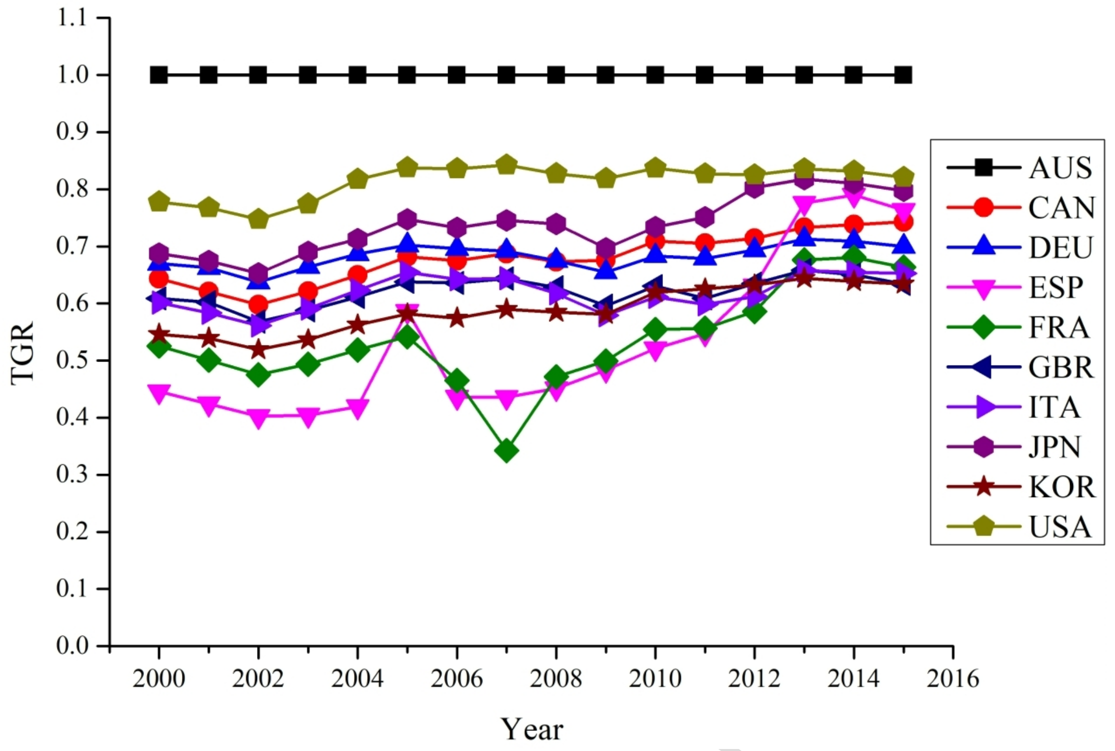
Results from **Table 3** show that the average value of the carbon emission welfare performance of G20 under the meta-frontier in the observation period is only 0.392, indicating that solving the triple dilemma of energy conservation, emission reduction and improvement of welfare has become a worldwide concern. This also illustrates the great challenge of pursuing green inclusive growth in a national economy, i.e., increasing overall welfare without harming the energy saving and emissions reduction (Egelyng et al., 2017; Berkhout et al., 2018). This outcome resonates with a study conducted by Fang et al., (2019) and provides clear indication that the growth pattern of G20 might not be green enough to guarantee long-term sustainable development. As such, the durational, trans-regional, and cumulative effects of carbon dioxide emissions cannot be ignored.

Results from Table 3, on the other hand, also reflect strong heterogeneity across groups. Specifically, under the MCP, the developing countries' WPCE was the highest with a yearly average score of 0.617, followed by the developed group with a number of 0.365, and the BRICS group with the lowest average score of 0.195. Three observations can be made based on this finding. First, it signifies that the developing countries have a remarkable "comparative advantage" of carbon productivity from the perspective of welfare (Zhu and Liu, 2011a). Second, it reflects the historical consequences and welfare loss caused by the harmful "treatment after pollution" development model of advanced countries represented by the United States (Zang et al., 2013). Last but not least, it highlights the disadvantages of welfare loss caused by the development model adopted in emerging markets that "prioritize growth as opposed to development" (Zhang et al., 2015a). As a result, the BRICS' carbon emission performance from the view of welfare is the worst outcome and shows a distinct disadvantage among leading countries in the world. The above results indicate the obvious welfare loss of the developed countries due to the accumulation of carbon emissions, and reveals the challenges the BRICS group faces in balancing the economic interests and environmental benefits in achieving overall well-being. Therefore, the traditional development mode of rapid economic growth at the expense of welfare loss is unsustainable.

For the individual countries, the average WPCE score of Australia, Argentina and Saudi Arabia, under both frontiers, reached 1, thus these countries' performances ranked top in both their sub-groups and the G20 overall. Brazil has a prominent advantage in the BRICS countries, especially in the traditional "BRIC" countries (namely China, Brazil, India and Russia). This result is consistent with the findings of Zhu and Liu (2011b), who show a "descending" order of wellbeing performance of carbon emissions for Brazil, India, China and Russia. Also note: in sharp contrast, China and the U.S, two of the world's largest carbon dioxide emitters, are both ranked at the bottom of the G20 (i.e., the 20th and 19th, respectively). These empirical results pose a fundamental challenge to the large emitters who need to implement green growth transformations and support enlightened climate governance. Further, this outcome also implies that the international community, especially the major economies with great social, economic and environment influences, should jointly undertake the historical mission of environmental conservation, emissions mitigation and enhancement of well-being.

With regard to TGR, the average annual score of the developing countries all reached 1, thus these countries are at the global frontier and represent the optimal performance levels of the G20 economies. Results indicate that the group identified as "developing countries within the G20" are at the technological frontier in terms of WPCE, and they have achieved a suitable balance in resource utilization, carbon emission control, and wellbeing. In other words, these countries can be seen as global "leaders" in terms of carbon emission welfare performance. The average TGR of the developed countries group was 0.681, second only to that of the developing countries group. A relatively prominent performance gap existed during the observation period, yet it also implies a certain room for performance improvement in such countries. Comparatively, TGR of the BRICS group was the lowest with an average score of 0.482, reflecting that the technical gap of the member countries is very significant. Fortunately, this finding also indicates that the BRICS countries have the greatest potential for performance improvement. If cutting-edge technologies in the field can be effectively absorbed and utilized, the performance of these nations will be greatly enhanced. Furthermore, developing economies represented by Argentina, as well as Australia, have achieved a "zero gap" in their performance, whereas the BRICS countries represented by Brazil and India and developed countries represented by Spain have shown relatively significant performance improvement potential.

In order to further identify the significance of the gap across the three groups, the nonparametric kruskal-wallis (KW) ranksum technique is used by referencing Du et al. (2015). Results show that TGR of different groups all rejected the original hypothesis under the condition of P=0.00, indicating that the heterogeneity of production technology is significant in the G20. This outcome also confirms that the heterogeneity issue cannot be ignored in the performance analysis of this study. In order to reflect the dynamic changes of TGR among the G20 countries, the TGR scores of each country across the observation period are presented in **Figure 1 and Figure 2**.

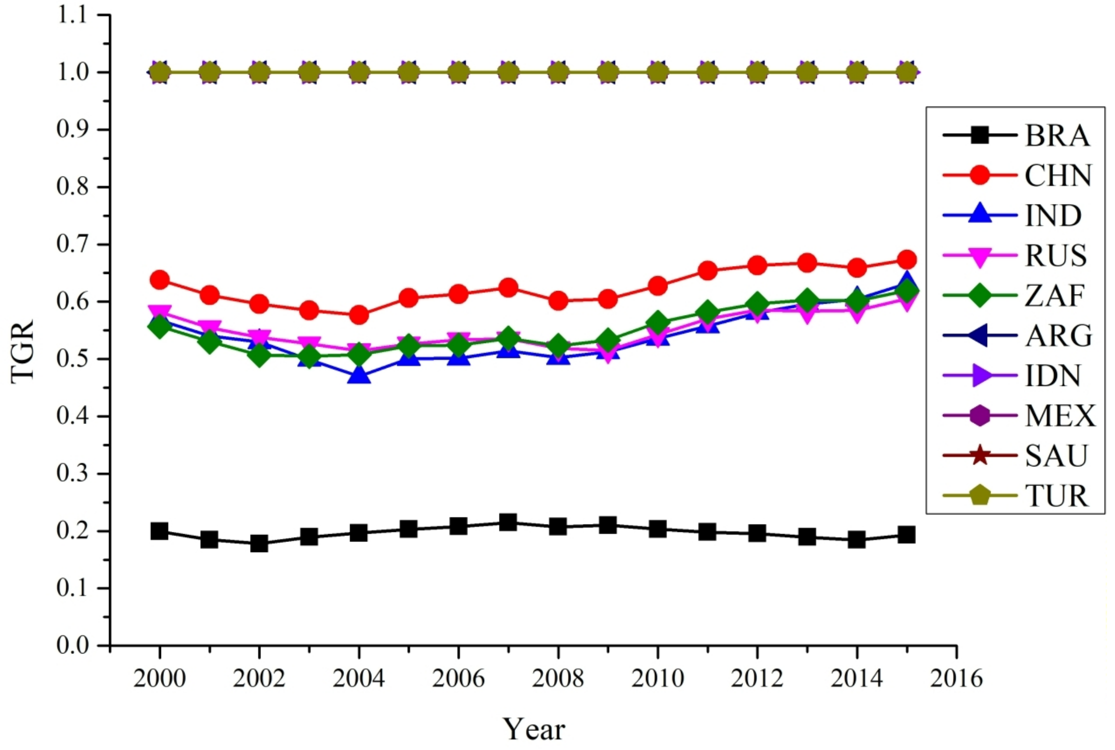


441

442 **Figure 1**. TGR scores for developed countries during the period 2000-2015.

443 Note: AUS (Australia), CAN (Canada), DEU (Germany), ESP (Spain), FRA (France), GBR (the 444 United Kingdom), ITA (Italy), JPN (Japan), KOR (South Korea), USA (the United States).

445



446

447 **Figure 2**. TGR scores for developing and BRICS countries during the period 2000-2015.

Note: BRA (Brazil), CHN (China), IND (India), RUS (Russia), ZAF (South Africa), ARG (Argentina), IDN (Indonesia), MEX (Mexico), SAU (Saudi Arabia), and TUR (Turkey). Specifically, TGR scores for ARG, IDN, MEX, SAU and TUR are all in 1 so the plots are overlapped in the figure.

As can be seen from **Table 3**, **Figure 1 and Figure 2**, a convergence trend has appeared for the TGRs on general as the TGRs of the countries are getting closer and the technology gaps are narrowing. This implies that although the existing technology gap is significant, green technological differences among countries are declining and the low-carbon technology gap is shrinking along with deepening of international cooperation, exertion of technological spillover, the formation of global climate governance framework and the consensus on green development.

In order to observe the level and determinants of performance loss, the annual mean values of MTI, TGI, and MI of each country and each group from 2000 to 2015 are calculated using formulas (4), (5) and (6). **Table 4** displays the average scores of total efficiency loss (MTI), technical inefficiency (TGI), and managerial inefficiency (MI) of the countries and groups during 2000-2015.

Table 4. Average scores of MTI, TGI, and MI of G20.

Country	***TGI***	***MI***	***MTI***	***Country***	***TGI***	***MI***	***MTI***
Australia	0.000	0.000	0.000	Argentina	0.000	0.000	0.00
Canada	0.192	0.399	0.591	Indonesia	0.000	0.739	0.739
Germany	0.090	0.714	0.805	Mexico	0.000	0.716	0.716
Spain	0.461	0.017	0.478	Saudi Arabia	0.000	0.000	0.000
France	0.306	0.35	0.656	Turkey	0.000	0.459	0.459
United Kingdom	0.178	0.529	0.707	**Developing countries**	0.000	0.383	0.383
Italy	0.237	0.376	0.614	Brazil	0.803	0.00	0.803
Japan	0.041	0.842	0.883	China	0.017	0.954	0.972
South Korea	0.242	0.413	0.655	India	0.077	0.835	0.912
United States	0.009	0.951	0.960	Russia Federation	0.089	0.801	0.890
Developed countries	0.176	0.459	0.635	South Africa	0.449	0.00	0.449
G20	0.154	0.453	0.608	**BRICS countries**	0.287	0.528	0.805

According to **Table 4**, the annual total performance loss (i.e., MTI) of G20 as a whole is 0.608, implying that welfare costs introduced by carbon dioxide emissions are significant. For the three groups, performance loss of the BRICS is the most serious, with an annual average value of 0.805 during the observation period, followed by the developed countries with an average performance loss of 0.635. Comparatively, the developing countries group achieved a smaller performance loss with an average score of 0.383. The above results are highly consistent with our previous measurement of carbon emission welfare performance and analysis of technology efficiency gap and this finding reaffirms the great potential of the BRICS countries in terms of future performance gains.

Regarding the sources of performance loss, the results in **Table 4** show the combined effect of technological inefficiency (TGI) and managerial inefficiency (MI) in the overall loss of G20. However, compared to technical constraint, the impact of managerial capacity is more critical as managerial and allocation inefficiency formed major obstacles for performance gains of G20. Such findings correspond to Wang et al. (2016a) and Wang et al. (2017b). It shows that compared with the "hard technology", optimization of "soft systems" and the increase of management ability are more important for the improvement of national carbon emission welfare performance.

For the three groups, performance loss in the developing countries is mainly attributable to inadequate managerial capability, and low allocation efficiency is the main driver of this performance loss. By contrast, TGI and MI both affected the BRICS and developed countries, yet the restriction of managerial capacity for performance improvement is more prominent and urgent as allocation inefficiency of the developed and BRICS groups accounted for 64.35% and 64.35% of group total performance loss, respectively. Therefore, the developing countries within the G20 subset have fully realized their technological potential and achieved the optimization of carbon emission welfare performance. As for the developed and BRICS countries, there is still potential for low-carbon technological progress and green innovation to be implemented. It is also critical for these countries to achieve transformation in terms of management concepts and system governance to facilitate and accelerate the improvement of welfare performance.

Four individual countries, China, U.S., India and Russia, also happened to be the world's four largest carbon emitters except for the European Union, experienced the highest performance loss during the observation period. Compared to technical levels, inadequate management capability and systematic efficiency have more significant negative impacts on their WPCE with an average contribution higher than 90% of the performance loss for all four countries. Compared with technological innovation, low-carbon management capability and institutional optimization have important practical significance for the realization of multiple goals such as energy conservation, emission reduction, social progress and comprehensive improvement of carbon emission welfare performance in the above mentioned countries.

5. Research conclusion and policy implications for China

5.1 Research conclusion

In this study, a unique perspective that brings human wellbeing and welfare as part of a carbon emissions performance is adopted in the assessment framework. A total factor framework is constructed to estimate the carbon emissions performance of the major global economies: the G20 group of countries. DEA-based hybrid measure model and meta-frontier analysis approach have been combined and utilized to observe the performance levels of each of these economies over time. The models are also used to provide a clear understanding of the determinants of carbon emissions and their impacts on welfare performance for each of the countries with divergent social, historical, geographical, economic, political and cultural backgrounds.

Major conclusions based on the empirical analyses of the G20 countries during 2010-2015 are as follows:

(i) Performance and technological heterogeneity of the G20. Based on the perspective of wellbeing and welfare, the G20's overall carbon emissions performance is comparatively low. This study also identifies the technological heterogeneity of the carbon emissions welfare performance as being significant in the G20 countries. Therefore, it is necessary to include the technological heterogeneity between economies into the analysis framework.

(ii) Performance of the sub-groups of G20. Carbon emission welfare performance of the developing countries within the G20 group was highly positive, which makes them the best practitioners in the G20. Correspondingly, the developed countries known for their economic powers are slightly inadequate in the dimension of welfare gains, while the WPCE of the BRICS countries with rapid growth were the lowest across the sub-groups.

(iii) Convergence trend of performance change in G20. Over time, the gap of welfare performance among countries has been shrinking, and performance loss for G20 as a whole has been declining. In addition, the empirical results show greater potential for the BRICS countries in performance improvement.

(iv) Sources for performance loss of G20. Although both the developed and BRICS countries are negatively affected by the inefficiency of technology and management capacity, poor management capability exists in all three groups and constitutes the main reason for performance loss.

5.2 Policy implications for China

China's carbon emission welfare performance shows the lowest score and the largest performance loss in the G20, which highlights the multiple pressures of domestic climate governance, ecological re-construction and welfare improvement. It also illustrates the great challenges China faces in international low carbon competition. However, from the static and dynamic analysis results of the tests, China has seen a narrowing of the gap, and is coming closer to the international frontier level. Meanwhile, the study shows that China has a huge gap and great potential in performance improvement. To achieve this goal, the country needs to release its potential in terms of technology, institution, and management. Based on the cross-country comparison findings in Section 4, countermeasures for China to enhance its WPCE are proposed below.

First, low-carbon technology innovation and application should be further advocated. After years of fast development under the domestic economic reform and international “open-door” policy (Curtis, 2014; Huang et al., 2016), China’s current energy efficiency innovation has entered a phase of diminishing marginal benefits (Wang et al., 2017a), where cutting-edge innovations in related fields are not satisfactory. Therefore, it is urgent to encourage and promote major technological breakthroughs and innovations in the fields of efficient use of traditional energy, carbon capture and storage, carbon sink capacity, new energy storage and the smart energy network, to further explore technological potential. In addition, the ultimate purpose of technology innovation is to serve the development of society. Therefore, the transformation, application, and promotion of low-carbon technologies as well as the accompanying innovations of business models should be consistent with the goals of improving human wellbeing. For example, China’s economy is largely dependent on coal consumption, thus clean coal technologies are crucial for meeting the country’s low-carbon targets. Although the *Action Plan for Clean and Efficient Use of Coal (2015-2020)* was issued three years ago, the development of expected technology progress is still at its early stage (Wang et al., 2018a). How to enhance the efficiency of coal utilization, especially in the power generation sector, is an urgent task faced by the government and the industry. For energy intensive industries such as thermal power, cement and iron & steel industries, continuous technology innovations are needed in order to achieve the promise of carbon peak at 2030 (Wang et al., 2018b). Financing mechanisms supporting the low carbon technologies should be largely promoted through policy support, including international climate financing, direct government spending and financial institutions participation.

Second, supply-side and market-oriented reform of energy systems should be further promoted. Due to its economic, environmental and social influences, the green transformation of energy systems has a substantial impact on the improvement of carbon emission welfare performance. Under the “New Normal” of China’s economy, (i.e., yearly growth rate slowdown from around 10% to a more modest 6 or 7% and a gradual optimization of economic structure (Chen and Groenewold, 2018; Yu and Du, 2018)), the role of market resource allocation should be further emphasized (Bin et al., 2018) and supply-side reform in energy field should be promoted (Zhang et al., 2018a). In so doing, resource depletion and environmental damage caused by deviation between price and value of resource products can be reduced (Denkena et al., 2018). Accordingly, several suggestions are proposed.

(i) Rapid and effective implementation of regulations on energy-conservation, energy efficiency and green energy development explicitly illustrated in a series of national legislations and bylaws such as the *Energy Conservation Law (2016 revision), the Renewable Energy Low (2009 revision), the Regulations on Energy Conservation of Public Institutions (2008)* and *the Regulations on Energy Conservation of Civil Buildings (2008)*.

(ii) Market-oriented tools for carbon emission reduction should be designed and promoted. Although, seven pilot cities have initiated carbon emissions, the effectiveness of the existing system is still controversial (Wang, 2016) and not well established given the absence of a national emission trading market. Accordingly, initial quota setting, pricing mechanism, and synergies between the trading systems requires further research and development.

(iii) A focus on the quality of development of renewable energies including wind power, photovoltaic and geothermal power is required as opposed to the pursuit of the scale of expansion. China has been committed to the development of clean energies and has become the leader in clean energy investment worldwide (BP, 2017). Such expansion is boosted by a series of supporting policies and national plans including the *13th Five-Year Plan for Renewable Energy Development (2017)*. However, effectiveness of renewable energy utilization is still in question and falling behind the expansion pace in quantity. Therefore, improve the quality of development approaches, such as increasing storage capacity, application, and improved utilization of renewables drawing from lessons learned in the developed economies.

Last but not least, the environmental governance system requires further improvements. For both China and the G20, improvement of management levels and capability are essential in performance enhancement and loss reduction. Therefore, it is necessary to comprehensively strengthen the capacity of environmental governance. Conventional thought that progress in technology plays the most critical role in energy conservation and emission reduction needs to be revisited. More attention should be paid to the promoting effect of institutional "soft constraints" represented by environmental management in addition to "hard technologies" represented by green tech (Wang et al., 2016a; Wang et al., 2017b). Therefore, a governance system related to environmental planning and management should be fully developed in China.

After years of effort and development in environmental regulation and management, China has made impressive progress in construction of an ecological society. Such achievements have laid a good foundation for future environmental policy formulation and environmental governance improvement. However, the country's green governance capability is still immature and should be further strengthened (Mu, 2018). Hence, a fully modernized national governance system and capacity for ecological environment has been expected for the mid-21st century in China (CCICED, 2018). In accordance, priorities should be given to non-technical innovations including green policy innovation, green management innovation, green social innovation, and green organization innovation. Optimizations, upgrades, applications, and expansions of such non-technical innovations will become a valuable source and guarantee to facilitate the country's low-carbon and conclusive development. Moreover, the important impacts of public participation and Environmental Non-governmental Organizations (ENGOs) should be further acknowledged and encouraged to improve the effectiveness of environmental governance system (Li et al., 2018; Zhang et al., 2019). In addition, a scientific and multinational evaluation system similar to the Worldwide Governance Indicators

(WGI) should be introduced and published on a regular basis to reflect the green governance achievement comprehensively and dynamically (Ward and Dorussen, 2015). As such, a visible and supervisory mechanism introduced by such an evaluating system will be constructed to form an outside "invisible hand" for better environmental governance (Wang et al., 2019).

5.3 Limitation and future studies

In addition, while this research offers some insights into the welfare performance of carbon emissions, the current study has several limitations that could be addressed in future studies.

First, the sample used in the research consists of only the 20 major economies of the G20. Future studies should expand the research sample to include small and medium-sized countries worldwide to observe and understand the development of WPCE from a wider and more international perspective. Comparative studies on other international groups such as the MINT countries (Mexico, Indonesia, Nigeria, and Turkey), the APEC countries (i.e., the Asia-Pacific Economic Cooperation members), and the OECD countries (i.e., Organization for Economic Co-operation and Development members) will help shed further light on the fundamental importance of wellbeing when included in evaluation of national performance.

Second, future studies could also explore other potential factors that explain efficiency loss other than technology gaps and managerial failure. Extended and novel models and techniques based on the hybrid measure and meta-frontier analysis are encouraged to take additional influencing factors such as structural change or scale of change into account for further analyses. This will bring new insights for understanding the determinants of WPCE variation.

Last but not least, in-depth case study can be conducted to form a supplement of pure quantitative research. Possible interesting topics of such case studies could be representative practices in certain countries with good WPEC performance, countries with fast growth rates in WPCE, or countries that excels in management or technological innovation.

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Appendix

Table 5. Country Profiles of G20

No	Region	Country	Abbreviation	BRICS	OECD	Developed/ Developing
1	Oceania	Australia	AUS	×	√	Developed
2	North American	Canada	CAD	×	√	Developed
3	Europe	France	FRA	×	√	Developed
4	Europe	Germany	GER	×	√	Developed
5	Europe	Italy	ITA	×	√	Developed
6	Asia	Japan	JAP	×	√	Developed
7	Asia	South Korea	KOR	×	√	Developed
8	Europe	United Kingdom	UK	×	√	Developed
9	North America	United States	US	×	√	Developed
10	Europe	Spain	ESP	×	√	Developed

11	North America	Mexico	MEX	×	√	Developing
12	Asia	Turkey	TUR	×	√	Developing
13	South America	Argentina	ARG	×	×	Developing
14	Asia	Indonesia	IDN	×	×	Developing
15	Middle-East	Saudi Arabia	SAU	×	×	Developing
16	South America	Brazil	BRA	√	×	Developing
17	Asia	China	CHA	√	×	Developing
18	Asia	India	IND	√	×	Developing
19	Europe	Russia	RUS	√	×	Developing
20	Africa	South Africa	ZAF	√	×	Developing

Note: For the classification of country types, a country is grouped as developed if it falls within the World Bank (2018) category of high income, and considered a country to be developing if it does not have a high-income economy. Please refer to https://data.worldbank.org/income-level/high-income?view=chart

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Highlights

- Welfare performance of carbon emissions (WPCE) are evaluated for G20 countries;
- A hybrid non-parametric evaluation and meta-frontier techniques are employed;
- Developing countries performed the best followed by developed and BRICS countries;
- Gaps of WPCE are non-negligible and sources of performance loss are divergent;
- Policy implications for China drawing on the cross-country comparisons are proposed.