Theoretical Economics Letters, 2022, 12, 1749-1772
https://www.scirp.org/journal/tel
ISSN Online: 2162-2086
ISSN Print: 2162-2078

Study on Updating the Spatial Strategy for the Carbon Neutrality Target of China

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How to cite this paper: Peng, C. Y., Zhou, W. X., Xie, G., & Ge, L. Y. (2022). Study on Updating the Spatial Strategy for the Carbon Neutrality Target of China. *Theoretical Economics Letters, 12,* 1749-1772.
https://doi.org/10.4236/tel.2022.126095

Received: October 23, 2022
Accepted: December 26, 2022
Published: December 29, 2022

Abstract

Allocating the national carbon neutrality target seems to be a difficult problem, in which there is a tradeoff between spatial equity and energy-based efficiency. However, if preferentially developing low-carbon economy for some areas rich in renewable energy sources is a national strategy considering domestic air mobility, then the relationship between equity and efficiency may be balanced. Based on Tone's Super-SBM model and "Aversion to CO_2"-SBM model with two different scenarios, etc., the results sustain that some provincial regions of China had a bigger contribution to carbon neutrality by improving the energy efficiency under a new hypothetical standard of very low carbon emissions, and the national industrial structure adjustment of China might obtain a longer strategic opportunity period. In addition, the author detected a seemingly bizarre idea from the vast sea of literature, and advisedly named it as "Herman Cycle". Deduced from the results and inspired by the "Herman Cycle", this paper proposes an alternative scheme or a strategic path for China to move smoothly towards carbon neutrality in the coming future.

Keywords

Energy Efficiency, Low-Carbon Dividends, Carbon Neutralization, Sustainable Development, Regional Development Policy

1. Introduction

For a long time, China has been highly dependent on fossil energy, and its consumption is increasing day by day. According to a report, non-fossil energies in China would account for more than 20% by 2030 and 40% - 45% by 2050 (Du, 2016).

The target of China's 2060 carbon neutrality set by its central government in

2020 is exciting. Usually, it is easy to think of a "broad way" to achieve this target by assigning tasks according to the regional economic level or population quantity for each provincial region. However, regions have different energy resource endowments, especially in energy resources. Not only a too simple way may inhibit the economic growth of some developed regions, but also let the regions potentially rich in renewable energy unable to give full play to their comparative advantages, which is easy to force the nation to fall into a "Carbon Neutralization Trap".

Despite the negative impact on air quality over the past few decades, coal had been an important input in driving China's economic growth and thus had been difficult to be reduced (Liu et al., 2021). However, energy-based economic efficiency in an underdeveloped region may be improved, while the economic growth opportunity may be obtained or created, if such a region happens to have more abundant renewable energy such as average long time sunlight with relatively cheaper development cost. The dilemma may be breakable.

It is believed that the future energy system had been shaping up based on several factors, and the first factor was thought of as improvements in energy-based efficiency (Bandyopadhyay, 2019). With the expansion of residential demand for electricity, enhancing the efficiency would be helpful for saving energy (Chen et al., 2019). A recent paper pointed out that the optimized path to achieving the goal of carbon peak, would mainly depend on the improvement of energy-based efficiency (He et al., 2021).

It is possible that fossil fuel can be replaced by "green power" earlier and faster in clean energy-rich areas, and then, the dilemma may be first alleviated locally. The dilemma is expected to be further alleviated, if such areas can provide extra "green power" to their adjacent areas, or the energy resource-poor regions under the background of the progress of UHV transmission technology. However, this needs to be systematically done by a national economic strategy with top-level design for a nationwide energy revolution.

The motivation of this paper lies in trying to explain the variation of China's energy efficiency, and looking for potential ways of transition from fossil energy to renewable energy. The policy implications may not only be expected to help stimulate an effect expressed by the Chinese idiom "Broaden Sources and Save Expenditures", but also help protect the Earth's biodiversity, as well as curb global warming.

In this paper, a well-tested idea of future energy direction is used as the theoretical basis for the sustainable development (Noyes, 1982). By using a generally recognized method of SBM—a type of DEA model, the energy efficiency of each provincial-level region in China has been measured for many years. In particular, by introducing "Aversion to CO_2" as an added hypothetical standard, the regional energy-based efficiency was re-estimated, and the regional ranking was found to slightly change. Through using the method of panel data analysis, it is found that the industrial structure has a significant impact on energy efficiency.

What should the sustainable direction of China be? This paper presents a new idea that may not be accepted by all, but must be enlightening, or even exciting, especially in giving full play to the development of renewable energy in specific areas. Under the assumption that the populous China needs to make corresponding or even bigger contribution to curbing the carbon emissions, this research is much meaningful.

The second part points out a dilemma in spatial decomposition for the carbon neutrality task, focuses on using a large number of data to measure the relative provincial energy-based efficiency in two different ways, tries to find some laws, and especially, uses geographic knowledge to tap the potential of the regions with low energy-based efficiencies. The third part adopts an empirical analysis method getting several results, and it is confirmed that FDI has a positive effect on the efficiency. The fourth part is about how to raise the efficiency based on two kinds of brave imaginations for some provincial regions over-dependence on coal, and one of them is an alternative design deduced from an exciting imagination of "Herman Cycle", which is partly verified after an unexpected technology of maintaining water for planting crops had been roughly successfully experimented in some semi-deserts. The last part is the conclusion and its policy implications.

2. Pursuing Energy Efficiency—Towards a New Era of Low Carbon Economy

The energy-based efficiency may be different among provincial regions, and the developed regions in them typically contribute more to the national efficiency. However, in a possibly coming new era of low carbon economy, some underdeveloped regions rich in renewable energy also deserve attention, because they may not only contribute to the sustainability of economic growth, but also have expected demonstration value for the energy transformation.

2.1. Theoretical Basis[1]

The logical starting point of this paper is that dominant countries should actively respond to the Glasgow Climate Pact (2022) on jointly addressing global climate change. China's manufacturing industry consumes a lot of energy, so it is necessary to evaluate the relationship between its share in all industries and the energy-based efficiency. The measures to solve the problem of over-reliance on coal may be diversified, however, if considering the domestic air flow (including CO_2) across provincial regions, the coping strategies with taking into account the economy will be very different from not considering this credible premise.

[1]This paper does not assume that the highly promising controllable fusion technology will be a reality in 30 to 50 years. In addition, the Earth has experienced ice ages for many times in its evolution process, but the period is usually very long. Therefore, this factor is also not directly considered in this paper. Wind energy should have a good prospect in coastal areas of China, but due to space constraints, this paper does not discuss it. As for nuclear power in China, the author does not hold an attitude.

How to use the very scattered solar energy resources and others intensively is related to the common destiny of humankind in future. Specifically, this paper focuses on taking Noyes's clear conclusion as the basic assumption or the starting point for new deduction, which is "whether solar energy fills a gap or eventually plays a leading and permanent role, the wise development and utilization of solar energy resources should be a high priority goal in human society" (Noyes, 1982). By the way, it should be noted that Noyes's work is very comprehensive in looking at the future of mankind and the Earth from an astronomical point of view, and some warnings have unfortunately occurred more than once, such as the Chernobyl Nuclear Accident (1986) and Fukushima Nuclear Accident (2011), which still seems to be worthy of high vigilance today[2]. However, the main purpose of this paper is focusing on discussing the selection of long-term strategic orientations for China's carbon neutrality goal from a perspective of researching the relationship between the energy-based efficiency and optimization of spatial equity, instead of the fate of all humankind.

Allocating carbon neutrality targets according to income or population principle among regions may be a good way for China. However, the regional interests are not always consistent with the nation, and some provincial regions with advantages in developing traditional fossil energy may not be eager to embrace using renewable energy. In the situation of still rising energy consumption, the selected direction should be making largely marginal effects through developing clean energies without carbon emissions, and enhancing the energy efficiency under a new evaluation criterion for a low-carbon economy.

2.2. The Super-Efficiency SBM Model

The super-efficiency SBM is an appropriate model to calculate relative efficiencies of selected units. By improving the measurement method of traditional DEA (Data Envelopment Analysis) model, it can achieve a higher discrimination degree than that of the ordinary SBM model or CCR model (Charnes et al., 1978; Tone, 2001). Recently, a paper used the super-efficiency SBM model to evaluate China's energy efficiency, but its purpose is to discuss the choice of urbanization paths (Yu, 2021). An earlier paper discussed similar topics, but what they referred to as "aversion output" actually is waste gas (sulfur dioxide), not directly related to CO_2 emissions, and more importantly, the purpose and ways of solving the problem in this paper are very different from their paper (Li et al., 2013).

The fractional form of the model is as follows, where $\bar{x}$ and $\bar{y}$ denote the undetermined weighted m-input and s-output vectors, respectively, x_0, y_0 are the corresponding given input and output vectors, and λ is the weighted coefficient vector to be solved for inputs and outputs, where $j = 1, \cdots, n$ (Tone, 2002; Du et al., 2010).

[2]This may not be a reason to abandon nuclear power utilization, but it should also be noted that fission-based nuclear resource is non-renewable and limited. A new phenomenon is that Japan seems to have an intention to restart its shut nuclear power plants.

$$\delta_I^* = \min \delta = \frac{\frac{1}{m}\sum_{i=1}^{m} \bar{x}_{i0} / x_{i0}}{\frac{1}{s}\sum_{r=1}^{s} \bar{y}_{r0} / y_{r0}} \tag{1}$$

Subject to $\bar{x} \geq \sum_{j=1,\neq 0}^{n} \lambda_j x_j$, $\bar{y} \leq \sum_{j=1,\neq 0}^{n} \lambda_j y_j$, $\bar{x} \geq x_0$, $\bar{y} \leq y_0$, $\lambda \geq 0$

The characteristic of this model is to distinguish efficiencies more strictly than other DEA models, such as CCR and ordinary SBM, because it is difficult for the latter two to estimate the efficiency accurately while some of the efficiencies have to be equal to 1, especially when the selected sample is small.

2.3. The "Aversion to CO_2"—SBM Model

The new objective function is as follow:

$$\rho^* = \min \frac{1 - \frac{1}{m}\sum_{i}^{m} \frac{\omega_i^- s_i^-}{x_{i0}}}{1 + \left(\sum_{r}^{s_1} \frac{\omega^{\text{good}} s_r^{\text{good}}}{y_{ro}^{\text{good}}} + \sum_{r}^{s_2} \frac{\omega^{\text{bad}} s_r^{\text{bad}}}{y_{ro}^{\text{bad}}} \right) \Big/ (s_1 + s_2)} \tag{2}$$

Different from formula (1), formula (2) can additionally reflect the impacts of negative output on the efficiency under a new hypothetic condition that a negative output variable is added, and this variable is considered as "the less, the better". For negative output, for example, if the excessive amount of CO_2 relative to normal output of GDP is too large, $s_r^{\text{bad}} / y_{ro}^{bad}$ will become larger, then its efficiency will inevitably become lower according to the new Tone's formula. The expression of new constraints is omitted here, but readers interested in the details of the method can refer to Tone's working paper (Tone, 2004).

In other words, when the concomitant CO_2 is regarded as a negative "output", the method of efficiency evaluation not only changes from single output to two types of outputs, but also needs to treat the new "output" of CO_2 as a harmful substance. In this way, the new hypothetic standard of evaluation for the energy-based efficiency is more appropriate, otherwise, it is much defective.

Specifically, just as Tone pointed out that "we can impose weights to the objective function to the model, where ω^{good} and ω^{bad} are the weights to the desired output s_1, and the undesirable s_2, respectively". In this paper, the author introduces a seemly unrealistic preference hypothesis for the first time, extremely sets the weights of ω^{good} and ω^{bad} to 0.1 and 0.9, respectively, then re-evaluates the efficiency, and obtains some enlightening results for reference. The purpose of such treatment is not to pursue absolute truths, but to make the calculated results between model (2) and model (1) have enough obvious distinction through reasonable exaggeration.

2.4. The Variation of Energy-Based Efficiency of China during 2003 to 2016

By using a large number of data, the author calculated the energy-based total factor efficiency of China's most provinces, municipalities and autonomous regions over the years from 2003 to 2016. To facilitate comparability, the efficiency is not calculated separately by year or region. The data from all regions in the years end to end are put together as a large sample to be calculated, and then the results are rearranged to the panel data form. This kind of processing with reliability ensures the comparability of the efficiency, fully guarantees the scientific nature of the panel data for analysis, and the accuracy of energy efficiency trends of variation.

As can be seen from **Figure 1**, China's average provincial energy efficiency showed an upward trend during 2003 to 2016, which is a gratifying achievement. However, the regional differences in energy efficiency are always large, which is closely related to China's coastal spatial development strategy (see the Appendix). For example, no matter which algorithm is used, the energy efficiencies of eight coastal provincial regions, including Guangdong, Beijing and Shanghai, were in the top list, and there was not any low efficient region in the coastal section. **Figure 1** also implies that one way for China to further improve energy efficiency and move towards carbon neutrality is to keep up playing the role of coastal section, but this may need to increase its reliance on nuclear energy if the coastal section can achieve a new miracle of economic growth by turning to an industrial zone with international competitive advantages in the absence of coal resource; another approach may be to maximize the comparative advantages of those arid or semi-arid areas with vast land resources, sparse population and light energy resources in energy transformation.

It is clear that most of the provincial regions where energy efficiency showed an obvious upward trend are located in Eastern China, and a few in Midwestern China (**Figure 2**)[3]. The efficiency in several regions averagely showed a little downward trend, and most of them are located in Western China (**Figure 3**). The trend of energy efficiency in some regions is not obvious.

2.5. The Ranking Changed after an Assumption of Hating Excessive CO_2 Is Introduced[4]

Table 1 reports the regional ranking status of energy efficiency, rise or fall. In other words, if the assumption of extremely hating carbon emissions is considered as a new standard, or if a region is less reliant on coal, then the region's relative efficiency will increase. Concretely, when the welcomed GDP and the disgusted CO_2 are boldly given weights to 10% and 90%, respectively, then the status of energy efficiency of some provincial regions may relatively rise or fall than before. For example, the rank of Shanxi Province would decrease for two places, because the province is much rich in coal, and relied on coal industry and its related industries, though this province's energy efficiency had been already low enough.

[3]China's eastern regions have a higher energy efficiency, but the total energy consumption is also large; China's nuclear energy is highly concentrated in the eastern section, and it seems that there is a new plan to continuously add nuclear power plants there.

[4]The data is reported in the Appendix.

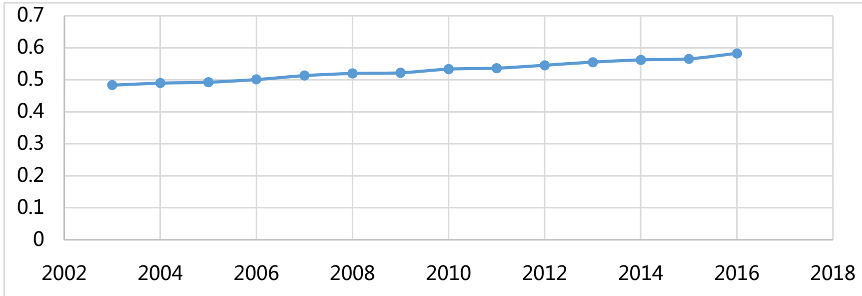

Figure 1. The upward trend of average energy efficiency of provincial regions since 2003 to 2016.

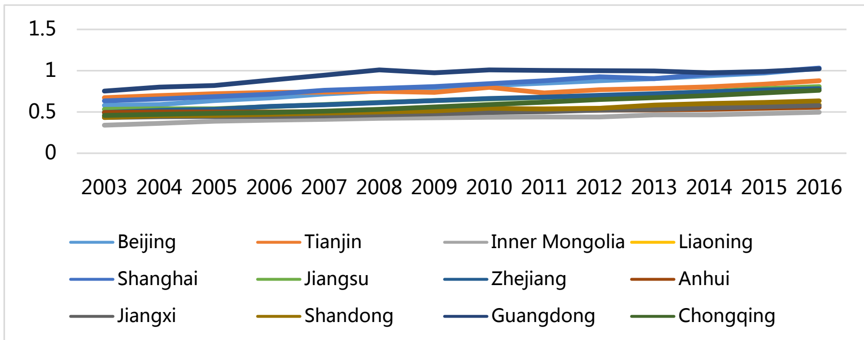

Figure 2. An obvious upward trend of energy efficiency of some provincial regions.

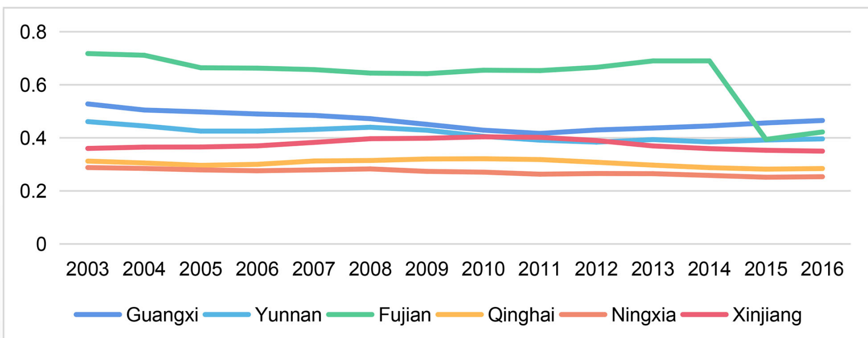

Figure 3. Downward trend of energy efficiency of some provinces or municipalities.

Table 1. The rise, constant or fall of the regional ranking between two standards.

Guangdong	0	Fujian	0	Hunan	2	Hebei	−2	Shanxi	−2
Shanghai	−1	Hainan	2	Anhui	−1	Henan	0	Gansu	1
Beijing	1	Heilongjiang	−1	Hubei	1	Guangxi	2	Xinjiang	−1
Tianjin	0	Chongqing	1	Jilin	−2	Shaanxi	0	Guizhou	−1
Jiangsu	−1	Shandong	−2	Jiangxi	0	Inner Mongolia	−1	Qinghai	3
Zhejiang	1	Liaoning	−4	Sichuan	6	Yunnan	1	Ningxia	0

Note: 1) The figures indicate that, the ranking of regional energy efficiency increased, unchanged or decreased after applying a new hypothetical standard of extreme aversion to carbon emissions; 2) The datum of Tibet is lacking in the table.

The ranking of Qinghai increased by three places than before under the new and extreme hypothesis. The fall of Shanxi's status and the rise of Qinghai's status indicate two types of actual development paths. To achieve the national carbon neutrality goal in future, the low carbon model with photovoltaic poverty alleviation in Qinghai seems more worthy of being praised[5].

The other good examples include Sichuan, Hainan, Guangxi, Hunan, Beijing, Zhejiang Gansu, Yunnan, and Chongqing, etc. For example, Sichuan Province ranks first in hydropower production in China, where hydropower should be an important reason for scrambling six places upward in the ranking of the energy-based efficiency (Table 1)[6].

2.6. It Is Possible to Improve the Regional Efficiency by Supplying "Green Power"

As shown in Table 1 and Figure 4, compared with the non-low-carbon standard, the energy efficiency ranking of Qinghai Province was still low under the low-carbon standard, but the ranking had risen by three places. This means that, with appropriate policy support, low-carbon standards might not only be conducive to the efficiency improvement of some underdeveloped regions, but also, if such regions happened to have a clear comparative advantage in supply of renewable energy, they would be also expected to obtain more and more "Low-carbon Dividends".

It is not difficult to select some appropriate local places for firstly aiming at the carbon neutrality target of the whole provincial region, such as some areas in Qinghai Province. Qinghai is located in the west section of the nation, its total population is only about 6 million, accounting for 0.4% of China, but its geographical area with extremely rich solar energy resources nears 8% of the national territory. Western China was thought as the best section to install solar photovoltaic power stations (Feng et al., 2021). This suggests that some of China's less energy-efficient regions may not only serve themselves, but also should be considered as the future engine of cleaner comprehensive production for the whole nation.

3. Panel Data Analysis for Explaining the Efficiency

It is necessary to explain why the average energy-based efficiency of China varied, and why the regional energy efficiencies were so different among regions during the selected sample period. The expected results will help China find its best way to a low-carbon economy.

[5]Shanxi Province may have other opportunities to improve its energy efficiency, which will be discussed later.

[6]However, in the Summer of 2022, there was a severe drought in Sichuan Province, and many rivers almost run dry, resulting in a serious shortage of hydropower. Fortunately, Gansu Province, which is relatively strong in photovoltaic power generation, timely delivered a lot of power to Sichuan during this period.

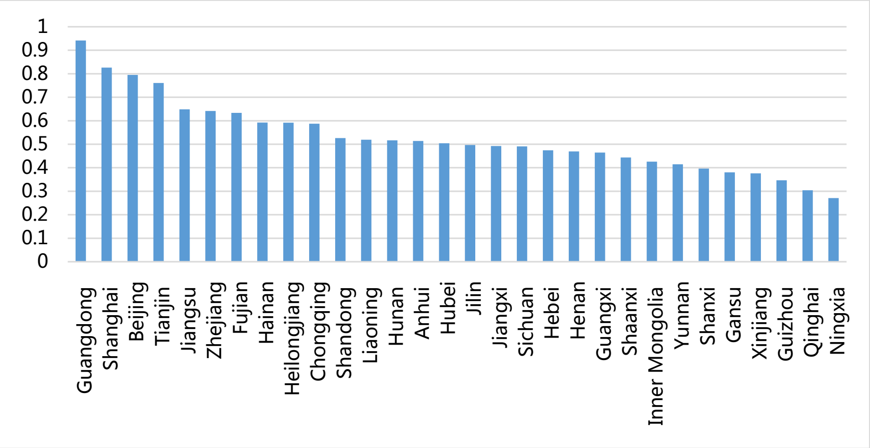

Figure 4. S-SBM energy efficiency, average value since 2003 to 2016, without assuming hating carbon emissions.

3.1. The Main Variables

The key explained variable is the energy-based efficiency. It is calculated by using the Input-Oriented type of Super-SBM Model and "Aversion to CO_2"-SBM Model with a large amount of raw data. Among them, the input variables include capital stock, employment, and total energy consumption, while the welcomed output variable is GDP (real value) in the first model. It is actually a kind of economic efficiency related to energy utilization, so it can also be called energy-related economic efficiency (EE). In the second model, the data of carbon emissions are estimated from fossil energy consumption such as coal, oil, etc.

Manufacturing industry is the main body of energy consumption, and it is closely related to China's economic performance and employment. Therefore, the variable of industrial structure is considered as the main explanatory variable, which is measured by the ratio of regional value added of manufacturing industry to GDP, and the other variables, including per capita power consumption level, are considered as control variables. Specifically, the indicator of foreign trade is the ratio of total imports and exports to GDP, the indicator of FDI is the ratio of foreign direct investment to GDP, and the calculations are based on the exchange rate of the current year[7]. The intensity of environmental regulation policy is measured by the ratio of investment for controlling pollution to GDP, and the electricity consumption per capita is the average consumption divided by population quantity. The indicator of research and development (R&D) is also calculated for hypothesis testing. The main original data are from China Statistical Yearbook, China Industrial Statistical Yearbook, and various regional statistical yearbooks, 2003 to 2016, etc. However, as an alternative, with the help of China's CNKI platform, the main original data required in this paper can also be obtained, but only Chinese keywords are required.

[7]In literature, FDI quality is usually measured from several dimensions: average size of foreign enterprises, total assets' contribution rate, and export, etc. We also used the original data to measure the quality of FDI, but because the result of this index is highly correlated with the quantity of FDI data, this index is not actually used.

3.2. Panel Data Analysis Model[8]

3.2.1. The Econometric Model

$$\log EE_{it} = c + \beta_1 \log STR_{it} + \beta_2 \log OPEN_{it}(-2) + \beta_3 \log FDI_{it} + \beta_4 \log ERP_{it} + \beta_5 \log PERPOWER_{it} + \beta_6 \log RD_{it} + \varepsilon_{it} \quad (3)$$

where, subscript $i = 1, 2, \cdots$ refers to 30 provincial regions except Tibet, t represents the year. EE_{it} represents the energy efficiency of region i in year t, and STR_{it} indicates the industrial structure. $OPEN_{it}(-2)$ stands for the foreign trade lagged two years; FDI_{it}, the share of foreign direct investment; ERP_{it}, the environmental regulation policy; $PERPOWER_{it}$, the power consumption per capita; RD_{it}, the ratio of research and development (R&D); and ε_{it}, the random term of the panel data regression equation.

By comparing the pros and cons of the panel data models through Hausman Tests, etc., this paper obtained a series of experimental results. Model 1 in Table 2 is more advisable after a series of simulation attempts while the carbon emissions are not considered. The impact of foreign trade on energy efficiency is in advance assumed to have a lag effect of two years. Though Model 2 in Table 2 is a different model, most of the results except foreign trade are almost no different from Model 1, so the detailed discussion on the econometric results in 3.2.2 is mainly based on Model 1[9]. It should also be noted that the foreign trade lagging two years in model 2 becomes no longer significant, but it becomes significant when lagging three years (not reported in the table), so it is still not easy to negate the role of this variable.

3.2.2. The Empirical Results of Model 1 with Interpretation

First of all, it is found that there is a significantly negative correlation between the proportion of manufacturing to all the industries and the energy-based efficiency, and its absolute value is not low (−0.122). It may indicate that China's industrial structure adjustment policies had played an important role in impacting on energy efficiency, while the manufacturing industry is the main user of energy[10]. For example, the ratio of manufacturing in Shanghai had been declining, though its manufacturing output value was still growing with an increasing energy efficiency trend (Figure 2).

This result is consistent with other papers (Wang et al., 2019). Specifically, the energy-intensive subsectors had great effects on reducing carbon emissions, and some scholars ever made a radical suggestion for a local province, Jiangxi, to greatly reduce the use of coal (Xu et al., 2017; Jia et al., 2019). However, though China's energy efficiency in manufacturing was low, there would be still a lot of room for improvement (Ouyang et al., 2021).

[8]If readers need it, the original data set used in this paper can be obtained from the author.

[9]Compared to Model 1, the absolute value of the variables in Model 2 becomes larger, except for the lagged foreign trade, which may mean that these variables are more important under the new hypothetic condition of low-carbon requirements.

[10]The ratio of manufacturing added value to GDP in China had been decreasing during the sample period.

Table 2. The results of panel least squares. The explained variable: Log (EE); Sample (adjusted): 2005 - 2016; Total panel (balanced) observations: 360.

GLS	Model 1 (for Super-SBM)	Model 2 (for Aversion to CO_2-SBM)
Explanatory variables	Fixed time and space model	Fixed time and space model
C	−0.744 (0.0000) ***	−1.410 (0.0000)***
LOG (STR)	−0.122 (0.0583) *	−0.239 (0.0064)***
LOG (OPEN (−2))	0.045 (0.0158) **	0.033 (0.1816)
LOG (FDI)	0.052 (0.0019) ***	0.081 (0.0004)***
LOG (ERP)	−0.021 (0.1120)	−0.030 (0.1044)
LOG (PERPOWER)	−0.133 (0.0006)***	−0.268 (0.0000)***
LOG (RD)	−0.004 (0.3087)	−0.011 (0.0547)*
R-squared	0.95	0.95

Note: 1) For the P values, ***, ** and * indicates level of significance of 0.01, 0.05 and 0.10 respectively; 2) The original scope was selected from 2003 to 2016. Due to the use of two-year lag of the foreign trade variable, most data used were mainly limited to 2005-2016.

Secondly, the policy of opening-up (foreign trade) has a positive relationship with the energy efficiency, but it has lag effects for about two years. The result is not contradictory with that increasing imports is an effective method of improving the efficiency for energy-intensive sub-sectors (Wei et al., 2020). It is also not inconsistent with that exports might play a big role in affecting the energy intensity (Zhu et al., 2020), and that there was a positive feedback between foreign trade and energy efficiency, such as in the textile industry, with imports impacting energy efficiency more than exports (Zhao & Lin, 2020), while another paper shows that the foreign trade significantly improved China's carbon productivity as well, i.e., reducing the proportion of carbon emissions per unit of GDP, mainly through imports (Zhang et al., 2018).

Thirdly, foreign direct investment (FDI) has a slightly positive effect on the energy efficiency with a small coefficient of 0.052[11]. The result is a little different from an opinion: although FDI contributed to energy efficiency in manufacturing, the high degree of FDI participation everywhere might temporarily hinder the improvement of energy efficiency (Zheng, 2021). Anyway, in the field of energy-intensive industries, the advantages might outweigh the disadvantages by effectively absorbing foreign direct investment.

Fourthly, there is a significantly negative correlation between the per capita electricity consumption and energy efficiency (−0.133). This seems to be a frustrating result while the consumption is still uprising in China. In order to maintain or improve energy efficiency, in the long-run, perhaps the government should strengthen the policy of saving electricity through a dynamic ladder price mechanism, or raise electricity prices regularly through specific taxes, especially

[11]Due to space limitations, causal analysis is omitted here. It shows that FDI is the cause, and efficiency is the result.

for high-income users who use excessive electricity beyond quotas, to reduce waste and make a direct contribution to reduce carbon emissions.

Fifthly, the environmental regulation variable is ineffective or has a slightly negative impact on the energy efficiency (coefficient, −0.021), while its p-value is 0.112, just a little more than 10%. Perhaps, regulation should directly highlight fuel tax, which not only helps save energy and reduce carbon emissions, but also helps improve income inequality (Jiang & Ouyang, 2017). In addition, the indicator of R&D is not found in improving energy efficiency in Model 1. The influence period of R&D on the efficiency may be long enough, which needs to be retested by scholars.

Sixthly, it seems insufficient to explain the rise of energy efficiency in China along with time. The two factors of foreign direct investment and the lagged foreign trade may play a small role in improving China's energy efficiency while their regression coefficients are positive but not large. A reasonable guess is that although some unknown factors related to the two factors may not be certain to help save energy, they are beneficial to the economic prosperity, and thus enhance the energy-base efficiency. Another speculative explanation is that the national policy of industrial structure adjustment might have played a certain positive effect, while some less developed regions were still stuck in the low energy efficiency trap because they undertook energy consuming industries transferred from developed regions. Nevertheless, it is still not ruled out other possibilities driving the energy-based efficiency, such as the rise of the information industry, the construction of high-speed railways nationwide, and even the foam-like prosperity of the real estate, etc., which needs further study. In addition, it is worth noting that in the case of introducing aversion to carbon emissions, the absolute value of several coefficients of corresponding variables becomes larger than before, and it should not be underestimated[12].

About all, in terms of time, China's energy efficiency improvement might be due to the effect of opening up or industrial structure adjustment; from the perspective of space, it might be that the developed regions had effectively promoted the efficiency, while the efficiency improvement in the underdeveloped regions had been restrained due to the large and growing per capita power consumption, etc.

4. Local Energy Revolutions Launched from Areas Rich in Sun Shine Is Feasible for Transition as an Alternative

It is not easy for China to continuously increase its energy-based efficiency. A simple path may be directly cutting the total energy consumption down sooner or latter. However, there is another option, perhaps, a better one, i.e., trying to let utilizing cleaner energy become an opportunity for local economy in some

[12]The coefficient of power consumption per capita has doubled. In the long run, GDP per capita would have a lasting positive impact on CO_2 emissions (Zhu et al., 2018). Some scholars argued that the progress on China's fossil fuel targets was stymied by continual coal development, which had negative implications for the Paris 2 degrees C limit (Carlson et al., 2021).

underdeveloped regions including through selling saved "green electricity" to outside, if it is possible.

4.1. It Is Necessary to Distinguish Two Situations of Commercial Potential

As we know from the previous part, some provincial regions are extremely inefficient in the energy-based economy. Regretfully, many of these regions are overly dependent on coal at the same time, even though some of them happen to have abundant renewable energy resources almost without utilization.

In this section, it is needed to distinguish two types of cases, and discuss them separately. One is to develop "green power" firstly in counties surrounding provincial capitals, especially in those capitals much rich in sunlight energy; another is to consider building super solar power stations in adequate semi-deserts, though the concrete sites may be a little far away from the provincial capital cities. This classification seems necessary, because under current conditions, the former is more feasible or easier to make direct effects in China, while the latter depends on new improvement of UHV transmission technology in order to further reduce power loss. However, if we consider the huge scale effect of power generation in the desert areas, the potential of the latter should be much greater in the long run (Ito et al, 2003).

4.2. Some Provincial Regions Should Take the Lead for the Carbon Neutralization

The abundant renewable energy resources in some underdeveloped areas may be intensively utilized with creating effects of scale and scope, only if most of the fossil fuels for power generation will be forbidden several months or years later, and the possible surplus "green power" supply can be expected to create new demands in future.

However, currently most regions still heavily rely on coals, including those having abundant sunshine resources with cheaper development cost. The problem may be from that one or several best regions have not been noticed, which are abundant in both coals and sunshine resources, such as Shanxi Province, Inner Mongolia Autonomous Region and Gansu Province, etc. However, the root of the problem should be that the economic advantages of traditional energy are too strong, while the policy support for using solar power is still insufficient.

For example, Shanxi Province, whose capital city is Taiyuan, has been China's most important coal-producing region with a dense power grids connecting to other provinces, but it is also much abundant in sunshine resources. The rank of Taiyuan City was No.4 among all the provincial capitals of China, and its quantity of the annual sunshine in 2020 was much approaching to Lhasa City, the highest one in the same year (**Figure 5**). Though it is not absolutely accurate when the data of the capital cities are borrowed to denote their corresponding provincial regions, it still has special significance because the capital cities are crucial in many fields for the provincial regions in China (**Figure 6**)[13]. Shanxi has a central location in China, in some of the abandoned coal mining areas, building large-scale photovoltaic power stations should be conducive to some traditional energy consuming industries, and may ultimately improve the regional economic efficiency based on energy.

The surrounding areas of the downtown of Taiyuan City, which almost have the same sunshine conditions as the city, may try to develop photovoltaic industry on a large scale, given that the central or provincial government would like to provide some special regional policies with enough incentives.

4.3. The Idea of "Herman Cycle" for Deserts Utilization Has Clearly Enlightening Values

Herman Wijffels is a Dutch economist. In a dialogue with others, he put forward

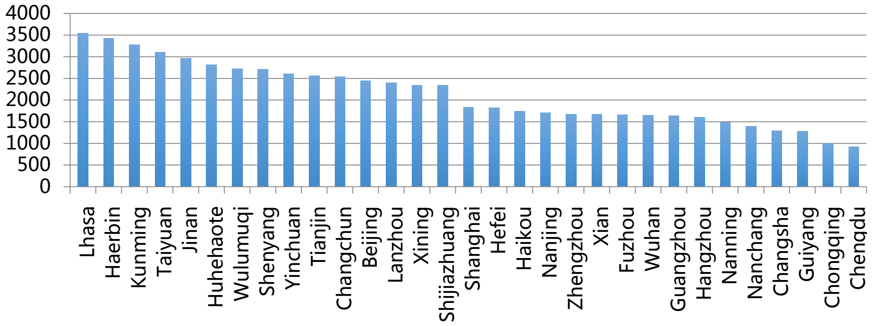

Figure 5. Rank of annual sunshine hours of 31 provincial capitals (descending order) in 2020. Data source: china statistical yearbook, 2021.

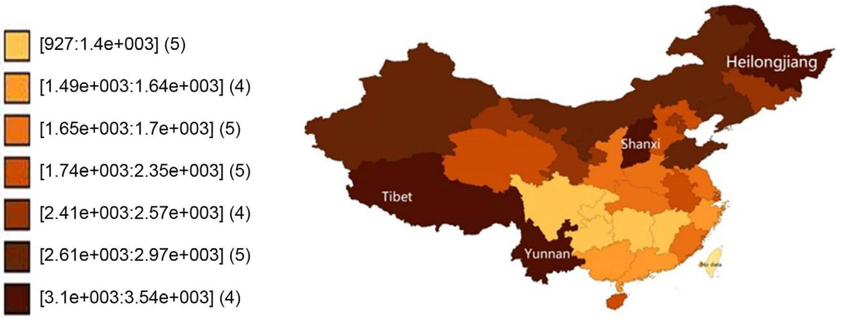

Figure 6. Annual sunshine hours according to provincial capital cities as proxy (2020). Notes: 1) The data are from *China Statistical Yearbook* 2021, and the darker the color, the longer duration of the average annual sunshine; 2) It is clear that Tibet, Heilongjiang, Yunnan and Shanxi, which correspond to the provincial capital cities of Lhasa, Harbin, Kunming and Taiyuan respectively, rank the highest, and the next level is the autonomous regions of Inner Mongolia and Xinjiang, whose provincial capitals are Hohhot (Huhehaote) and Urumqi (Wulumuqi), and other regions; 3) There is no comparable datum for Taiwan, and the color of the mark on Taiwan Island has nothing to do with the duration of sunshine.

[13]For example, Xinjiang Uygur Autonomous Region with huge desert area may be under valued according to this principle, but at present, the rich sunshine in the arid deserts far from the economic centers seem more difficult to be utilized.

an academic idea: "In the next 30 to 40 years, we should find ourselves in a state of excess energy. If we have surplus, we can use it for other purposes, such as seawater desalination. Then, this water can be used to irrigate the desert, and then, to increase the available biomass. In this way, not only can we provide more food, but also provide materials for manufacturing new products, chemicals, etc." (Durston & Baggerman, 2017). However, unless the new energy has been widely utilized at that time, the general assumption of "energy surplus" may be difficult to occur, except for some small areas. Nevertheless, the idea of "Herman Cycle" still has great enlightening value[14]. Any scholar can learn from this way of thinking and create similar or even more feasible ideas.

In a working paper named O*il Consumption Peak Coming in Advance and the Energy Utilization Philosophy* promulgated in Chinese in 2007, one author of this paper ever argued that solar tower power stations built in deserts would have the brightest prospects in Northwestern China in theory[15]. Recently, several modern solar power stations really have been successfully built in a famous county in a desert edge named Dunhuang, and the coal-fired power generation there will almost be not needed eventually.

4.4. An Enlightening Idea of a Imaginary "Clean Circular Economy" for China

As far as China is concerned, due to the large area of deserts and semi-deserts in the western section, it is undoubtedly feasible to consider firstly building (large-scale) solar power stations in some semi-desert areas. It is even worthy of using electric trains or long pipelines with green power facilities to fetch fresh water from low-lying places in semi-humid areas, transporting or transferring it back to those semi-desert areas, and building some small reservoirs or artificial lakes there. These reservoirs or man-made lakes can be used for fish farming, and in their surrounding areas, people can plant drought-enduring plants, and even raise animals, etc. It is also necessary to adopt the most advanced drip irrigation technology. The crops usually have high economic value, because it is unnecessary to apply chemical fertilizers and pesticides in their production process, and the products may be more popular with rich consumers. The surrounding areas seem easy to become tourist attractions, attracting tourists to go sightseeing, and some new or modern small towns are expected to be formed, thereby creating more economic values[16].

It is needed to remind again, **Figure 6** does not completely reflect the real distribution of China's annual sunlight resources, only indicates the general situation of various regions represented by provincial capital cities in 2020. In fact, averagely, the deserts or some plateaus have the longest time of sunshine all year

[14]Perhaps, it is more in line with Academic Convention to name it as Wijffels Cycle, but the first name of Herman seems to be more interesting.

[15]http://cpfd.cnki.com.cn/Article/CPFDTOTAL-SYDD200710001010.htm.

[16]However, if large-scale pilot projects are carried out, specific cost-benefit analysis is also needed to conduct risk assessment.

round. They are mainly located in the no-man's lands in Xinjiang, Gansu, Tibet and other regions, with a vast area, which are far from being used. Eventually, some selected areas in the deserts and semi-deserts are expected to play a decisive role in the process of China's pursuing carbon neutrality[17].

4.5. An Emerging Technology Is Helpful to Form a Circular Economy for Semi-Deserts

Fortunately, a new technology popularly known as "Convert Sand into Soil" was successfully tested in some desert areas in China, and this information can be confirmed from Internet news in 2018, named "Scientists Successfully Convert Sand into Soil"[18]. This means that some semi-desert areas with little rainfall have a greater chance of partly becoming oases in some extent, and even producing agricultural products, because the water retention conditions around plant roots can be improved.

Despite some academic queries, the existing facts show that this technique is undoubtedly a great blessing for those areas that had degenerated into deserts due to human excessive activities in history (Yi et al., 2022). However, these testing projects are neither combined with photovoltaic power generation, nor related to stable supply of fresh water, which needs to be constantly transmitted from other places into the deserts or semi-deserts. In other words, a new concept of "spatial integration" may also be likely to become a reality or need to have a try. In particular, if such degraded deserts due to historical overexploitation can partly restore vegetation or be used to grow crops, they will additionally absorb the stocked carbon dioxide on the Earth, which is directly conducive to the carbon neutrality goal. In future, if an integrated project is considered and carried out, and large enough, it is likely to have both symbolic and significant impacts on China's realization of carbon neutrality earlier (**Figure 7**).

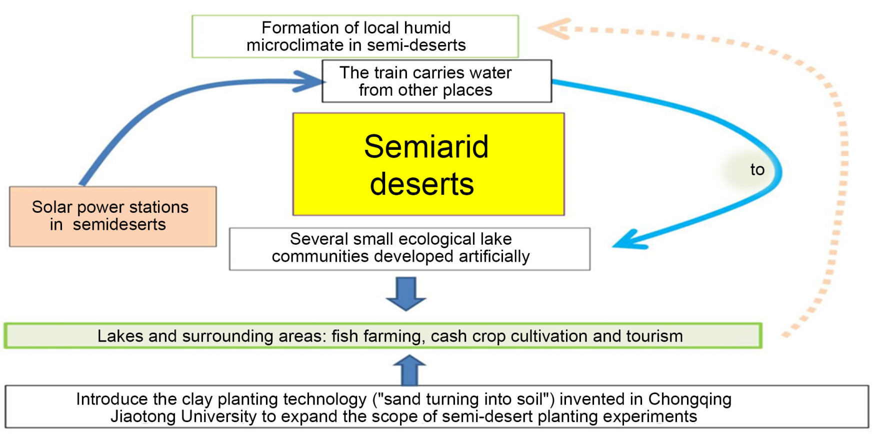

Figure 7. An enlightening hypothetical scene for semi-deserts with low population density.

[17]In the Kubuqi Desert of Inner Mongolia, China, with the help of photovoltaic power generation projects, small oases have emerged, which is commendable.

[18]https://www.dnaindia.com/technology/report-scientists-successfully-convert-sand-into-soil-2252342.

Though the content in the Figure 7 may be far from perfectness, its principle is logically consistent with the "Herman Cycle", so it should also have much important reference value for academic peers. In addition, the hypothetical scene answers the question of why there may be excessive energy in the future, as assumed by Herman, at least in a specific nation, without necessarily expecting a rare technology of controlled nuclear fusion to become true quickly.

Above all, it is possible to achieve improvement of the energy-based efficiency under low-carbon requirements, through giving full play to its advantages of vast territory with richer sunlight, while both the average economic level and energy efficiency in the western and northern sun light belts are still much low. This shows a potentially new economic path, which is very different from the traditional way of thinking style. If such areas take the lead in greatly replacing traditional fossil energies with competitive renewable energy, and even sell surplus green power to neighboring provincial regions, then both the spatial equity and energy efficiency can improve with a high possibility, especially under the new standard of much low carbon emissions. However, there is still a lack of corresponding policies and incentive mechanisms, which needs to study deeply in future.

5. Conclusion and Policy Implications

5.1. Conclusion

5.1.1. The Main Path for the Carbon Neutrality Goal of China Should Be Focusing on Renewable Energy Especially If China Identifies It as a New Comparative Advantage

Allocating regional targets of carbon neutrality seems to be a difficult problem, in which there is a tradeoff between equity and efficiency. However, if the low-carbon economy such as stimulating the scale and scope effects of solar power generation including photovoltaic poverty alleviation or revitalizing rural areas with developing renewable energy is assumed as a basic national policy, then it will be possible that both spatial equity and economic efficiency can be improved. The results sustain that some middle or western regions of China may have a bigger or earlier contribution to the national carbon neutrality by improving the energy efficiency under a new standard, i.e., highlighting the strategic position of regions rich in renewable energy resources. The national spatial industrial structure adjustment of China may obtain a longer strategic opportunity period. Utilizing solar energy sources in the vast semi-arid regions in the Huangtu Plateau in the Northwest, or desertification areas in the vast Qinghai-Tibet Plateau in the West caused by improper historical development, should be one of the broad pathways in the future.

5.1.2. The Mid-Western Part of China Has a Bright Prospect to Combine the Sustainable Development Path with Increasing the National Share of "Green Electricity"

The tradeoff in abandoning fossil energies may become opportunities in both regional economic growth and environmental improvement, if responsible policies for low-carbon economy including photovoltaic poverty alleviation are assumed as a basic national strategy. For example, if some of the Mid-Western regions with backward economic level and extremely rich solar resources take the lead in replacing fossil energy with cleaner energies, the domestic cycle of the economy will be stimulated, and then the overall energy-based efficiency may also be pulled up, leading to improve both spatial equity and energy efficiency. In short, Mid-Western China can make greater contributions to the national carbon-neutral mission and achieve Pareto improvements in development, increasing spatial equity, and improving the efficiency under the new hypothetic standard of much hating carbon emissions. One thing is certain, for the national goal of carbon neutrality, it is necessary to upgrade the traditional Western Development Strategy since 1999.

5.2. Policy Implications

5.2.1. The China's Dilemma in Phasing Coal down Can Be Alleviated First in Specific Areas Ready to Help Provide "Green Power" to Neighboring Regions

In view of the negative impact of carbon emission constraints on the manufacturing industry, it is necessary to combine domestic industrial transfer policy with new energy policy for regional integration development. However, the areas undertaking industrial transfer should generally be rich in renewable energy resources, and more policies should be adopted to support the local efforts to encourage the development of renewable energy, so as to make them more competitive in the power market. Selling "green power" to other regions not too far away is both beneficial to oneself and others, a win-win situation.

In addition, in order to improve the energy-based efficiency, the policy of "attracting foreign investment" seems still necessary, especially for the underdeveloped regions.

5.2.2. Some Regions Rich in Coal Resource Such as Shanxi Has Potentially Comparative Advantage in Solar Energy Utilization for Both Economic Transition and Carbon Neutrality

This should be an attractive result according to the basic theory of economics, because even if coal exploitation is forcedly reduced by new policies, the provinces rich in sunlight may also make progress in economy. Through carbon transaction markets and others, the new industries with low carbon emissions would grow naturally, and even some saved "green power" can be sold to other provinces which are poor in annual sun shines. The surrounding counties of some provincial capital cities with better infrastructure may develop solar energy earlier or more widely, while the richness degree of regional annual sunlight resources is roughly showed (**Figure 6**). In other words, Shanxi, Inner Mongolia and Xinjiang, etc., which have huge coal resources and production capacities, also have strong comparative advantage of renewable energy in the new era of carbon neutrality, and even may go faster than other provincial regions much poor in renewable energy. It seems to be a simple and reasonable way!

5.2.3. Building Solar Power Stations in Some Places in the Semi-Arid Zone of China Should Be a Good Strategy with Breeding Local Ecological Economies

A good example is that in the boundary belt between the Qinghai Tibet Plateau and the Huangtu Plateau in Northwestern China, a large-scale ground photovoltaic power station has been built in a sparsely populated village with ravines, and crops can also be successfully planted in the station[19]. Undoubtedly, this project can help achieve local poverty alleviation or even prosperity. For this village, the produced power is far more than its own needs. At least, it no longer purchases power from outside or broadly uses coal. In fact, it can provide a large amount of green power to other areas. This means that the economy and the ecology are not necessarily contradictory.

Under the background that China's industrial structure had a negative impact on the energy-based efficiency, it may be not realistic to arrive the national carbon neutrality goal through heavily weakening the domestic manufacturing industry. However, it is also possible to first start a *Regional Energy Revolution* by upgrading the traditional spatial strategy, including the so called "One Belt and One Road", the Western Development Strategy, etc., to extend the life period of some energy-intensive factories, given that Western China with low population density is almost the most backward economy, but clean energy resources such as solar energy are almost the most abundant. At least, the photovoltaic poverty alleviation policy in rural areas including those located in Qinghai Province is much worthy of praise or support.

5.2.4. It Is Not Necessary to Let It Completely Follow the Population Quantity or GDP Level among all the Regions Regarding the Spatial Allocation of Carbon Neutrality Targets[20]

If the task of carbon neutrality is decomposed according to the total population or GDP of each region, and if the energy consumption of such a region is large enough in population or GDP, it will undertake more emission reduction obligations. However, this will either encourage overexploitation of nuclear energy, or inhibit the development of renewable energy sources[21]. Resources such as uranium 235 for nuclear power are also limited, and non-renewable, therefore,

[19]In the anoxic plateaus, especially in their desert areas formed by historical overexploitation, it has been proved that the construction of large-scale photovoltaic projects can produce comprehensive effects. For example, photovoltaic panels block the sunshine and reduce the evaporation of water under the surface of land, and after the clean water is used for regular cleaning of the photovoltaic panels, the leaking water will cause weeds to grow, not only to increase oxygen concentration and absorb carbon dioxide in the air, but also to be used for freely herding sheep by local peasants among the panels.

[20]In the real World, in order to forcibly control energy consumption, some factories had to be temporarily shut down, resulting in a lot of new problems. An example is that a lot of energy-consuming enterprises in Eastern China were forced to shut down while the wind power capacity had to be largely abandoned in the Northwest in the Autumn, 2021.

[21]It seems inevitable that China's coastal nuclear power would be further incentivized under the national carbon-neutral goal, but nuclear power has safety risks, and it is debatable.

this way of thinking should not be optimal.

Electricity can be transmitted to use in close or far places, and the key is whether the new-added electricity is "green". If some underpopulated or underdeveloped regions with the richest renewable resources are asked to take on greater responsibilities with specific supports for the national task of carbon neutrality, it will be possible to further reduce the operating costs of renewable energy through stimulating its scale and scope effects, along with enhancing the energy-based efficiency.

5.2.5. The "Herman Cycle" or a Slightly Different Version May Have an Enlightening Value for China to Move towards the Goal of Carbon Neutrality Smoothly

The "Herman Cycle" seems to be only a mirage that has not been really realized. However, it deserves high attention while Herman Wijffels' vision for the global future was focusing on the arid deserts (Durston & Baggerman, 2017). The arid deserts have almost no life all year round, but there are extremely rich sunlight resources.

As far as China is concerned, it seems that a circular economy model similar to the imaginary "Herman Cycle" may be created. This paper puts forward a new idea, which may not be perfect, but it should have enough enlightening value. China's semi-desert areas formed due to historical overexploitation are very large and sparsely populated. It is expected not only to make greater contribution to the national power supply, but also to make such areas a slightly more livable through delivering fresh water based on "green power" production. In other words, China's industry distribution and its big share in coastal regions may change in some extent, and the inter-regional gap may be gradually shortened in the process of determinedly moving towards the great goal of carbon neutrality. Although this new idea will be difficult to be fully realized, it is not impossible to try to test within a certain range and period. Innovation should be encouraged. This also means that a good conclusion that a strong decoupling action in China between national per capita GDP and carbon emissions is notable, which pointed out that economic development can coexit with carbon emission reduction (Xu & Bai, 2022).

In short, China still has many rooms for improvement in energy-based efficiency, while a number of regions with relatively low efficiencies have great potential, especially in the fields of largely producing "green power" and transmitting "green power" to other provinces. As China is moving towards its "Dual Carbon" goals for 2030 and 2060 respectively, some areas rich in solar energy all year round are expected to achieve the goals much earlier. Wise national and local supports for those selected areas can serve multiple purposes, including creating new jobs, driving technological progress related to "Dual Carbon", and more.

Highlights

- The regional proportion of manufacturing industry seems to hinder the energy-based efficiency in China.

• The tradeoff between spatial fairness and efficiency in allocation for carbon neutrality mission will be weakened through selectively developing renewable energy among different regions or areas.

• Optimizing the distribution of economy with updating spatial strategy for wisely utilizing renewable energy is suggested.

• It indicates the effect of "Resource Curse" in Shanxi Province that is rich in coal is breakable.

• It puts forward giving full play to the comparative advantages of areas rich in renewable energy by scale and scope operation.

• Modestly, it suggests creating a new small ecological circular economy model in specific areas such as some semi-deserts.

CRediT Authorship Contribution Statement

This is a team work, and the responsibility is mainly undertaken by the corresponding author, Wenxing Zhou.

Acknowledgements

We sincerely thank the organizers of the Beijing Energy Conference 2021, as well as two anonymous reviewers, but for any possible error, the author is solely responsible. We also thank the anonymous reviewers of this journal for their insightful comments.

Conflicts of Interest

The views expressed in this paper are solely the authors' own and do not necessarily reflect the views of the supporting agencies and authors' affiliations. The authors alone are responsible for any remaining deficiencies. The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix (Efficiency Data, Descending Order)

Regions	A-SBM (1:9)	Regions	S-SBM
Guangdong	0.851761	Guangdong	0.941782
Beijing	0.649508	Shanghai	0.826069
Shanghai	0.634362	Beijing	0.794947
Tianjin	0.513051	Tianjin	0.760854
Zhejiang	0.426494	Jiangsu	0.648484
Jiangsu	0.423028	Zhejiang	0.641625
Fujian	0.405826	Fujian	0.633506
Hainan	0.402515	Hainan	0.592358
Chongqing	0.379658	Heilongjiang	0.591749
Heilongjiang	0.355097	Chongqing	0.587399
Hunan	0.324310	Shandong	0.526092
Sichuan	0.318100	Liaoning	0.519364
Shandong	0.310636	Hunan	0.516728
Hubei	0.309221	Anhui	0.514082
Anhui	0.308350	Hubei	0.504499
Liaoning	0.306939	Jilin	0.496552
Jiangxi	0.305446	Jiangxi	0.492248
Jilin	0.293982	Sichuan	0.491122
Guangxi	0.282299	Hebei	0.474477
Henan	0.281146	Henan	0.469537
Hebei	0.275438	Guangxi	0.464724
Shaanxi	0.254655	Shaanxi	0.443771
Yunnan	0.251668	Inner Mongolia	0.425750
Inner Mongolia	0.241952	Yunnan	0.414520
Gansu	0.228349	Shanxi	0.396334
Qinghai	0.223559	Gansu	0.380265
Shanxi	0.221958	Xinjiang	0.376113
Xinjiang	0.214884	Guizhou	0.346332
Guizhou	0.201284	Qinghai	0.304244
Ningxia	0.178800	Ningxia	0.270718