Research Article

Input–output efficiency model of urban green-energy development from the perspective of a low-carbon economy

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Abstract

With the acceleration of urbanization, cities are the main targets for carbon neutrality and urban energy is the terminal of energy consumption and the integration point of various energy systems. Therefore, there is a need to promote the development of urban green energy and achieve low input and high output to achieve a low-carbon economy in cities. Previous studies have not considered the input–output efficiency of urban green-energy development. This study fills this gap. Based on the economic–energy–environmental framework, an input–output efficiency-evaluation index system for urban green-energy development was constructed. Based on improved data-envelopment analysis, a comparative evaluation of the input–output efficiency of green-energy development was carried out in 30 provinces in China in 2019. Considering the differences in regions, the development of urban green energy in different provinces was classified. From the perspective of a low-carbon economy, economic growth factors and environmental constraint factors were set. Together with the generalized Divisia index approach, the input–output efficiency optimization directions of urban green-energy development were obtained. The results showed that the input–output efficiencies of urban green-energy development in Jiangsu, Zhejiang, Fujian, Inner Mongolia, Ningxia and other provinces and cities were relatively high. Provinces with faster economic development and higher environmental carrying capacity have advantages after optimization and will become pilot areas for the development of urban green energy. This research provides a reference for the development of urban green energy in various provinces from the input and output perspective.
**Introduction**

China is the world’s second-largest energy producer and consumer. Its rapid growth in energy supply provides important support for the economy, but also puts pressure on the environment [1]. Under the guidance of the dual-carbon goal, to promote the sustainable development of energy, the Chinese government is working towards the implementation of energy-saving and emission-reduction strategies to alleviate greenhouse-gas emissions. The main methods of implementation are to vigorously develop renewable energy, improve energy efficiency, reduce emission-reduction costs and ultimately promote the rapid development of a low-carbon economy [2]. With the acceleration of urbanization, CO₂ emissions in urban areas account for >60% of all emissions [3], hence urban areas will become the main front of carbon neutrality. The main emission sectors of CO₂ are electricity, heat production and transportation. Urban energy systems, as the terminal of energy consumption and the integration point of various energy systems, will undertake the important task of green-energy transition. Therefore, it is necessary to rationally plan the development of urban green energy to achieve a balance between resource input and output [4]. This will be necessary for future cities to achieve green-energy transition.

Currently, research on urban green energy is mainly divided into macro and micro research. From a macro perspective, Wang et al. [5] reviewed and analysed the situation and challenges faced by China’s green-power development and the key points of the green-power development model using the consumption of new energy as the core. Lazaroiu et al. [6] proposed that the planning of urban green-energy systems on short and medium timescales was a major concern for policy makers. The analysis of possibilities and directions for urban development should focus on the integration of renewable energy sources within urban boundaries. These studies elaborated on the importance of urban green energy and the development path of urban green energy in the future, but did not make further research on specific energy links. From a micro perspective, studies have suggested the development of urban green energy from different perspectives. From a policy perspective, Romano et al. [7] explained the effectiveness of green policies based on the development stage of countries. The results confirm that not all policies promote investments in renewable sources and their effectiveness depends on the development stage of the countries. From the economical aspect, Zhang et al. [8] constructed an evaluation system for green finance development and suggested that the relationship between green finance and sustainable-energy development can be quantitatively analysed. From the technical aspect, Xu et al. [9] analysed and defined green-energy technology and its applicability from the all-around perspectives of the symbiosis of economy, society, environment, and science and technology; and correspondingly constructed an evaluation index system. Some scholars have integrated multiple aspects, such as environment, economy and society, etc., to build an evaluation system for urban green-energy.
Li et al. [10] developed a multi-criteria framework to assess the priority of renewable-energy development and utilization in China for the economy, society and the environment. Wang [11] defined green-power-grid content and evaluated the conservation of energy from power generation, transmission, distribution and electricity sides, emission reduction from atmospheric environmental impact, water environmental impact, noise influence and solid-waste influence. Li et al. [12] measured the sequence and differences in the development and utilization of renewable energy in different regions for carbon-emission reduction and economic benefits.

In summary, most studies are limited to green-energy supply links or green-energy consumption links. There is a lack of research on the analysis of urban green-energy development from the perspective of the entire industry chain. The energy industry involves a chain: upstream, midstream and downstream. Therefore, it is necessary to study the development of urban green energy while considering the entire industry chain to promote urban renewable energy. However, current research on urban green energy involves a relatively limited area. As an important country that promotes carbon neutrality, China needs to re-examine the relationship between resource input and value output for urban green-energy development considering carbon neutrality. This is conducive to the rational planning of urban resources within each province. Based on this background, the present study establishes an input–output efficiency model of urban green-energy development from the perspective of a low-carbon economy.

Based on the analysis framework of the economy–energy–environment, we first establish an input–output efficiency-evaluation index system for urban green-energy development. Second, the input–output efficiency is measured using the improved data-envelopment analysis (DEA) model. Finally, based on economic growth and environmental constraints, the generalized Divisia index approach is used to optimize the input–output efficiency and a path for future urban green-energy development is proposed. Both the theoretical method and the practical significance are innovative.

1. The input–output efficiency indicators of urban green-energy development

1.1 Urban green-energy development framework based on economy–energy–environment

Energy is necessary for the production and life of human society and is also an important foundation of the national economy [13]. Energy resources can be used as a driving force to promote rapid economic growth. The environment is the ultimate energy carrier. When energy development and utilization are not balanced, energy development becomes an important cause of environmental damage. Therefore, energy, economy and environment (3Es) form an interrelated complex system [14]. The coordinated development of the three is not only a simple linear combination of energy, economics and environmental systems, but is also a dynamic process in which various subsystems influence and restrict each other. This relationship is shown in Fig. 1.

Under the framework of the 3Es, the development of urban green energy ought to coordinate with the
relationship between the economy and the environment to achieve overall development. From an energy perspective, the proportion of green energy must be increased to promote an increase in the proportion of terminal electricity. From an economic perspective, it is necessary to optimize the social and economic structure, transform the growth model of the social economy and achieve a low-carbon, circular and sustainable economy. From an environmental perspective, increasing investment in environmental governance to achieve full-stage control of greenhouse-gas emissions will lead to overall development. In future, the development of urban green energy will be dominated by comprehensive urban energy planning. The development model has shifted from an extensive development model of ‘high input, low output, high consumption, and low efficiency’ to an intensive development model of ‘low input, high output, low consumption, and low pollution’. Ultimately, to improve input–output efficiency, the development of urban green energy realizes the unification of resource input and value output, and realizes energy conservation and emission reduction, as shown in Fig. 2.

1.2 Input–output of urban green-energy development

1.2.1 Input of urban green-energy development

Energy involves a chain: upstream, midstream and downstream. Therefore, the development of urban green energy is reflected in the three links of supply, grid and consumption. We discuss the resource input for urban green-energy development for each of the three:

(i) On the supply side, the input to urban green-energy development is mainly reflected in the development and utilization of renewable energy. The proportion of renewable-energy installed capacity and renewable-energy power generation are typical indicators. Compared with traditional fossil fuels, the development of renewable energy can control greenhouse-gas emissions from the source, leading to significant environmental benefits.

(ii) On the power-grid side, smart grids have significantly promoted the development of urban green energy. The large-scale construction of smart grids will facilitate the cross-regional transmission of green energy and promote the large-scale consumption of renewable energy. Therefore, the input on the grid side is mainly reflected in the level of renewable-energy accommodation. The levels of renewable-energy accommodation and smart substations are typical indicators.

(iii) On the consumption side, electric energy substitution is the goal of urban green-energy development and an effective means to promote green-energy accommodation. Therefore, increasing the proportion of electricity in the terminal field is an input to the consumption side of urban green-energy development. The number of terminal electricity substitutions is a typical indicator.

1.2.2 Output of urban green-energy development

Based on the energy–economy–society framework, the development of energy is closely related to the economy and environment. Therefore, the development of urban green energy is not only reflected in the transformation of energy utilization methods, but also has an important impact on economic development and environmental improvement. Environmentally, the development of urban green energy will result in the effective integration of resources and effective control of greenhouse gases. Economic development depends on the development of the energy industry. The development of green energy leads to an increase in the gross domestic product (GDP) and effectively reduces energy consumption per unit of GDP. Therefore, based on the energy–economy–society framework, we reflect the value output of urban green energy based on energy, economy and the environment.

1.3 Input–output efficiency indicators of urban green-energy development

Based on the analysis in Section 1.2.1 and considering the population of different provinces, we selected four indicators of renewable energy: installed capacity, renewable-energy consumption, terminal power substitution and population. The economic-value increments, CO2 emissions and electricity consumption in the whole society were selected as output indicators. The input–output indicator system for urban green-energy development is presented in Table 1.

2 Input–output efficiency model-based DEA

From the perspective of efficiency evaluation, the core connotation of efficiency is the optimal allocation of
resources, i.e. the proportional relationship between input and output. The higher the degree of optimal resource allocation, the higher the efficiency [15]. The efficiency of urban green-energy development refers to the ability of urban green energy to obtain the maximum output or obtain an output with the minimum input cost. Therefore, multi-input and multi-output DEA can be used to evaluate the efficiency of urban green energy [16].

DEA is a modelling method that uses linear programming to evaluate the effectiveness of the input and output of the same unit [17]. This method does not need to estimate the functional relationship between the input and output variables. DEA uses linear programming to calculate the production frontiers of all decision-making units (DMUs) and then judges its efficiency based on the relative positions of each decision-making unit and the production frontier. Based on the above principles, the decision-making unit at the front of production is efficient; otherwise, it is inefficient. The basic principles are shown in Fig. 3. There are four DMUs: A, B, C and D. Each point is a situation of input and output. Using the DEA model, the curve connecting points A, B and C is the production frontier, referred to as the efficient line. All invalid points are at or below the efficiency line [18].

Based on the DEA principle, Charnes et al. [19] proposed the Charnes–Cooper–Rhodes (CCR) model and transformed it into an equivalent linear programming model such as Equation (1) through the Charnes–Cooper change. Suppose there are \( n \) evaluation units (or decision-making units); there is an input vector \( x_i = (x_{i1}, x_{i2}, \ldots, x_{im})^T \) composed of \( m \) input indicators in the \( i \)-th evaluation unit DMU. There is an output vector \( y_i = (y_{i1}, y_{i2}, \ldots, y_{is})^T \) composed of \( s \) output indicators. \( w = (w_1, w_2, \ldots, w_m)^T \) and \( z_u = (u_1, u_2, \ldots, u_s)^T \) is the weight vectors of the input and output indicators. \( E_i \) is the efficiency of the \( i \)-th evaluation unit DMU. In the model, \( w^T \) and \( \mu^T \) are the decision variables. If \( E_i = \mu^T y_i = 1 \) is satisfied, the DMU is called the DEA valid. If \( E_i < 1 \), DMU is considered to be non-DEA valid:

\[
\begin{align*}
\text{max} & \quad E_i = \mu^T y_i \\
\text{s.t.} & \quad w^T x_j - \mu^T y_j \geq 0 \quad (j = 1, 2, \ldots, n) \\
& \quad w^T x_j = 1 \\
& \quad w \geq 0 \\
& \quad \mu \geq 0
\end{align*}
\]

(1)

However, the DEA model often uses the idea of ‘self-interest’ for evaluation. That is, we choose to calculate the relative effectiveness of the most advantageous weight. To address this shortcoming, an improved DEA cross-efficiency-evaluation model is proposed. The main idea is to calculate the efficiency-evaluation value \( E_{ij} \) of the \( j \)-th evaluation unit DMU through the weight \( \mu \) of the best input index of the \( j \)-th evaluation unit DMU and the weight \( w \) of the best output index. Then, \( E_{ij} = \frac{\mu^T y_j}{w^T x_j} \). The improved DEA model is as follows:

\[
\begin{align*}
\text{max} & \quad E_{ij} = \mu^T y_j \\
\text{s.t.} & \quad w^T x_j - \mu^T y_j \geq 0 \quad (j = 1, 2, \ldots, n) \\
& \quad w^T x_j = 1 \\
& \quad \mu^T y_j = E_{ii} w^T x_i \\
& \quad w \geq 0 \\
& \quad \mu \geq 0
\end{align*}
\]

(2)

Table 1: Input–output efficiency indicators of urban green-energy development

| Indicator name             | Indicator type | Variable                                      | Unit  |
|---------------------------|----------------|-----------------------------------------------|-------|
| Input indicator           |                |                                               |       |
| Renewable-energy installed capacity | Energy input | The proportion of renewable-energy installed capacity | %     |
| Renewable-energy accommodation | Energy input | The proportion of renewable-energy accommodation | %     |
| Terminal power replacement | Energy input  | The proportion of terminal power consumption | %     |
| Output indicator          |                |                                               |       |
| Population                | Non-energy input | Total population at the end of the year | 1000 people |
| Economic-value increments | Expected output | GDP                                           | 100 million yuan |
| Electricity consumption   | Expected output | Electricity consumption of the whole society | 10 000 kWh |
| CO₂ emissions             | Unexpected output | CO₂ emissions                               | 10 000 tons |
This model indicates that under the condition that the evaluation result of the evaluation unit DMU, is maximized, the evaluation results of other evaluation units are also optimized.

3 Input–output efficiency optimization model based on low-carbon economic goals

3.1 Generalized Divisia index approach

The idea of the exponential decomposition method is to decompose the change of the explanatory variable into a combination of changes of different factors, and then determine the weight according to different decomposition methods to identify the contribution degree of each factor index. The Divisia index was originally proposed by Francois Divisia in 1925 [20] as a factor-decomposition method that considers continuous time intervals. Vaninsky [21] further expanded the Divisia exponent decomposition and proposed a generalized Dickens exponent-decomposition method. This method can solve the paradox problem caused by ignoring the dependence between factors. In the generalized Divisia index approach, the target variable Z is expressed as a function \( f(X) \) of the factor index \( X_1, X_2, \ldots, X_n \) connected with each other through the following equation system:

\[
Z = f(X) = f(X_1, X_2, \ldots, X_n). \quad (3)
\]

\[
\Gamma_j (X_1, X_2, \ldots, X_k) = 0, j = 1, \ldots, k. \quad (4)
\]

The generalized Divisia index approach model is as follows:

\[
\Delta Z | X | \Gamma = \int \nabla Z^T (I - \Gamma X \Gamma^T) dX \quad (5)
\]

where \( \Delta Z | X | \Gamma \) is the contribution of the influencing factor \( X \) to the change in the target variable under the condition that each factor has the constraint relationship of Equation (4). \( \nabla Z \) is the gradient vector. \( T \) is transpose. \( \Gamma \) is the identity matrix. \( \Gamma_X \) is the Jacobian matrix of \( \Gamma_j (X_1, X_2, \ldots, X_n) \). \( \Gamma^T_X \) is the generalized inverse matrix of \( \Gamma_X \). \( dX \) is a diagonal matrix composed of \( dX_i, dX_j, \ldots, dX_n \).

3.2 Economic growth factor

We use GDP as an objective function. The total GDP is equal to the sum of the GDP of each region. When the index is decomposed, GDP and the final consumption expenditure are linked to the population. Therefore, the objective function of the economic growth factor is as follows:

\[
Y = \sum^n_{i=1} Y_i = \sum^n_{i=1} x_i \lambda_i = \sum^n_{i=1} (x d_i) \lambda_i = x \sum^n_{i=1} d_i \lambda_i \quad (6)
\]

where \( x \) is the total consumption expenditure, \( x_i \) is the regional consumption expenditure, \( d_i = \frac{y_i}{Y} \) is the share of the total consumption expenditure in each region and \( \lambda_i = \frac{y_i}{Y} \) is the share of the regional final consumption expenditure in the regional gross output value.

Taking the population into account, the economic growth factor and the objective functions is transformed into

\[
y = \frac{Y}{N} = \frac{X}{N} \sum^n_{i=1} d_i \lambda_i = \hat{x} \sum^n_{i=1} d_i \lambda_i. \quad (7)
\]

where \( y \) represents GDP, \( N \) is the total population and \( \hat{x} \) is the per-capita final consumption expenditure. Then, the fastest increase direction vector of GDP under the constraints is as follows:

\[
d_{\text{GDP}} = \text{Proj}_{\text{H}} \nabla \hat{y} = \langle u_1 - \bar{u}, u_2 - \bar{u}, \ldots, u_N - \bar{u} \rangle \quad (8)
\]

\[
d_{\text{GDP}} = \frac{d_{\text{GDP}}}{\|d_{\text{GDP}}\|} \quad (9)
\]

3.3 Environmental constraint factor

Similar to the economic growth factor, when the index is decomposed, CO2 emissions are linked to carbon-emission intensity and final consumption expenditure. The objective function of the environmental constraint factor can be established according to the principle of the generalized Divisia index approach:

\[
c = \sum c_i = \sum x_i c_{ai} = x c x \sum \left( \frac{x_i c_{ai}}{x c} \right) = x c x \sum d_i r_{ai} \quad (10)
\]

\[
c = \frac{c}{c_0} = \sum d_i r_{ai} \quad (11)
\]

where \( c \) is the total CO2 emission, \( c_i \) is the CO2 emission of the area \( i \), \( c_{ai} \) is the carbon-emission intensity, \( c_{ai} \) is the carbon-emission intensity of the area \( i \), \( r_{ai} = \frac{c_i}{x_i} \) is the share of regional carbon-emission intensity and \( c \) is the carbon-dioxide emission rate in the base year.

Similar to the economic growth factor, the anti-gradient projection vector of the environmental constraint factor was obtained as follows:

\[
d_e = -\text{Proj}_{\text{H}} \nabla c = \langle r_{c1} - \bar{r}, r_{c2} - \bar{r}, \ldots, r_{cn} - \bar{r} \rangle \quad (12)
\]

\[
d_e = \frac{d_e}{\|d_e\|} \quad (13)
\]

3.4 Optimization model of the input–output efficiency

The purpose of urban green-energy development is to find a balance between the economy and environment, and to achieve the coordination and unity of the two. Therefore, the purpose of optimization is to obtain a highly positive correlation vector between the projection gradient of economic-value increments and the back-projection gradient of CO2 emissions. In the direction of this vector, urban green-energy development will achieve economic growth and environmental improvement, which will greatly improve input and output efficiency:

\[
\max \mu y + \text{correl} (d, d_{\text{GDP}})^2 + \text{correl} (d, d_e)^2 \quad (14)
\]

s.t. \( d = \alpha_1 d_{\text{GDP}} + \alpha_2 d_e \)

\[
\alpha_1, \alpha_2 \geq 0
\]

\[
\alpha_1 + \alpha_2 = 1
\]
\[ \hat{d} = \frac{d}{\|d\|} \]  

(15)

The model needs to meet the constraint advancement of the input–output model (see Equation (2)) and meet the constraint conditions based on economic growth factors and environmental constraints, i.e. Equation (15).

4 Case study

4.1 Basic data

According to the principle of data availability, we used the data of 30 provinces across the country in 2019 as the research object. Therefore, it is necessary to collect basic data, such as GDP, consumption expenditure and the total population. These data mainly come from the ‘China Statistical Yearbook’ and the ‘National Economic and Social Development Statistical Bulletin’. In addition, data on energy and environment, such as CO₂ emissions, electricity consumption of the society, the proportion of renewable energy, the transmission capacity of the grid and the proportion of terminal electricity, are required. These are mainly derived from the ‘China Energy Statistical Yearbook’, ‘China Electric Power Yearbook’, ‘China Environmental Statistics Yearbook’ and environmental annual reports of power companies (see the online Supplementary Data).

4.2 Result analysis

4.2.1 Input–output efficiency results based on the improved DEA model

Based on the established DEA model and the improved DEA model, the input–output efficiency of urban green-energy development in a total of 30 provinces in 2019 was estimated. This is shown in Figs 4 and 5.

In the traditional CCR model and the improved CCR model, the input–output efficiency of urban green-energy development in Jiangsu, Zhejiang, Fujian, Inner Mongolia and Ningxia is relatively high. This shows that the two DEA models are consistent. Additionally, for the economically developed provinces such as Jiangsu and Zhejiang, the level of economic development can drive the green development of urban energy to a certain extent. Provinces such as Inner Mongolia and Ningxia, with better natural conditions, also have sufficient resource endowments, such as wind power and photovoltaics, to develop green energy.

Through the improvement of the DEA model, the input–output efficiency of urban green-energy development in some provinces has changed. Some provinces that performed well in the evaluation of the traditional DEA model did not perform well in the improved model. These provinces include Shandong, Shanxi, Henan, Hubei, Liaoning and Guangdong. On the contrary, some provinces with poor performance in the traditional DEA model evaluation performed well in the improved DEA model, such as Jiangxi, Jilin, Fujian and Hunan. Their performance was attributed to the improved DEA method that can fully consider the connection between the evaluation units, while avoiding ‘self-interested’ thinking in the traditional model and making the evaluation more comprehensive and objective. This enables the DEA cross-efficiency-evaluation model to correct the deviation of the traditional DEA model evaluation results; however, the input–output efficiency of most provinces in the traditional DEA model and the improved DEA model are basically the same, which illustrates the effectiveness of the DEA model in this study.

4.2.2 Regional classification of urban green-energy development

Considering the differences in different regions, the development of urban green energy in different provinces was
classified based on the measured input–output efficiency. The classification standard of a province was the performance of input variables in all provinces (ranking result) and the performance of input–output efficiency in each province (ranking result). The difference between the mean value of the input–output efficiency ranking of the urban green-energy development of each province and the number 16 is the ordinate; the difference between the three input variables of the urban green-energy development of each province and the number 16 is the abscissa; the three input variables are the proportion of renewable-energy installed capacity, the proportion of renewable-energy consumption and the proportion of terminal electricity, as shown in Figs 6–8.

Based on the performance of input variables and the input–output efficiency of each province, the provinces are divided into four categories of ‘input–output type’. They are ‘input advantage–output stable type’, ‘input disadvantage–output aggressive type’, ‘input disadvantage–output conservative type’ and ‘input advantage–output potential type’.

Regarding the indicator of the proportion of renewable-energy installed capacity, Zhejiang, Jiangsu and other provinces are committed to promoting the development of renewable energy with the help of their economic and spatial advantages. Provinces such as Guangxi and Qinghai take advantage of their natural resources to develop green energy under local conditions, such as photovoltaics, wind power and hydropower. The development of urban green energy in these provinces belongs to the stage of ‘input advantage–output stable’. Owing to space resources

Fig. 5: Input–output efficiency of urban green-energy development based on the improved DEA.

Fig. 6: Relationship between the proportion of renewable-energy installed capacity and input–output efficiency.
and renewable-energy constraints, renewable-energy installed capacity is relatively low in areas such as Beijing and Tianjin. However, because of their technical advantages and other factors, these areas overcome this disadvantage and have high input–output efficiency, therefore belonging to the ‘input disadvantage–output aggressive’ stage. Provinces with superior natural conditions, such as Xinjiang, Guizhou and Yunnan, belong to the stage of ‘input advantage–output potential’ due to technical, economic and other factors; the input and output efficiency is low. For Jiangxi, Jilin and other regions, the proportion of renewable-energy installed capacity is relatively low and other aspects cannot compensate for the shortcomings, so these belong to the stage of ‘input disadvantage–output conservative’.

Regarding the proportion of renewable-energy accommodation, provinces such as Ningxia, Guangxi, Qinghai and Fujian, with favourable natural conditions, are mainly in the stage of ‘input advantage–output stable’. These provinces are rich in renewable energy and are an important source of energy. Therefore, they are mostly locally absorbed. Most of the provinces in the ‘input disadvantage–output aggressive’ stage are economically developed cities that overcome the shortcomings in this aspect.
such as Guangxi, Yunnan, Guizhou and Xinjiang are part of the ‘input advantage–output potential’ stage with superior natural conditions but need to strengthen power-grid construction. Other parts such as Shanghai, Chongqing and Guangdong are economically developed with low environmental benefits. However, owing to their high demand and high carbon-dioxide intensity, the input–output efficiency is low. Provinces such as Liaoning, Shanxi and Jilin that use traditional energy as their main energy input are in the ‘input disadvantage–output conservative’ stage.

The indicator of the proportion of terminal electric energy mainly reflects the electric energy substitution and demand-side management level of the city. Therefore, economically developed regions such as Beijing, Shandong, Jiangsu and Zhejiang provinces are in the stage of ‘input advantage–output stable’. This stage also includes some provinces rich in renewable resources, such as Qinghai and Guangxi, indicating that renewable-resource power generation is an important power input for such cities. However, Tianjin, Hebei and other regions have insufficient power-substitution levels and rely on their economic advantages to be in the ‘input disadvantage–output aggressive’ stage. Although Xinjiang, Jiangxi and other regions have a relatively high proportion of terminal power, due to environmental benefits and economic constraints, the input and output efficiency of green-energy development is low; these cities therefore belong to the ‘input advantage–output potential’ stage. For provinces such as Shanxi, Jilin and Shaanxi that use fossil energy as the main energy source, the input level of this indicator is relatively low. These provinces therefore belong to the stage of ‘input disadvantage–output conservative’.

4.3 Input–output optimization based on low-carbon economic goals

The growth of the economic level and the limitation of environmental carrying capacity have an important impact on the development of urban green energy. The input–output efficiency is optimized based on economic growth factors and environmental constraint factors for urban green-energy development. An optimized two-indicator projected gradient is shown in Figs 9 and 10.

![Projected gradient of economic growth factor](https://sampleimage.com)

**Fig. 9:** Projected gradient of economic growth factor.

![Back-projection gradient](https://sampleimage.com)

**Fig. 10:** Back-projection gradient of environmental constraint factor.
For the economic growth factor, Jiangsu, Beijing, Zhejiang, Chongqing, Shandong, Fujian and other eastern coastal cities or municipalities have high projection gradients. Inland provinces such as Ningxia, Inner Mongolia, Jilin and Liaoning, and north-eastern provinces have lower projection gradients. Regarding environmental constraints, the environmental carrying capacity of the populous provinces, such as Hebei, Shandong, Henan and Shanxi, are relatively poor. Municipalities with high levels of environmental governance, such as Tianjin and Beijing, and provinces with sparsely populated areas, such as Ningxia and Qinghai, have a better environmental carrying capacity.

Considering the impact of the economy and the environment, the input–output efficiency of urban green-energy development is optimized based on low-carbon economic goals. These results are presented in Fig. 11. The overall ranking is consistent with the results of the improved CCR model, but provinces such as Beijing, Zhejiang, Tianjin, Shanghai and Fujian, with faster economic development and higher environmental carrying capacity, have advantages in ranking. These cities will lead in the development of urban green energy in the provinces of China.

5 Conclusion

In the context of a low-carbon economy, we constructed input–output efficiency-evaluation indicators for urban green-energy development based on the economic–energy–environmental framework. First, an improved DEA model was used to measure the input–output efficiency. Second, the input–output model was optimized based on the low-carbon economic goal. The following conclusions were drawn:

(i) In the DEA model and the improved DEA model, the input–output efficiency of urban green-energy development in Jiangsu, Zhejiang, Fujian, Inner Mongolia and Ningxia is relatively high. This shows that the improved DEA model is consistent with the ranking results of the traditional DEA model, but the improved DEA model effectively corrects the deviation of the traditional DEA model.

(ii) Based on the relationship between the input variables and the input–output efficiency of each province, the provinces are divided into four categories. Each province has advantages and disadvantages of developing green energy and proposes future improvement direction and development paths. For economically developed provinces, the level of economic evolution can drive the development of urban green energy to a certain extent; therefore, these provinces should focus on their economic advantages and develop green-energy technologies. Provinces with better natural conditions, such as wind power and photovoltaics, should be fully utilized to develop green energy.

(iii) Through the optimization of input–output efficiency by economic growth factors and environmental constraints, provinces such as Beijing, Zhejiang, Tianjin, Shanghai and Fujian that have relatively high economic levels and strong environmental governance levels will become leading regions for urban green-energy development.

Supplementary data

Supplementary data is available at Clean Energy online.

Conflict of interest statement

None declared.
Credit Author Statement
Hongliang Wu contributed to conceptualization; methodology, software, data curation, writing-original draft preparation. Ling Wang helped in writing-reviewing and editing. Daoxin Peng contributed to visualization and investigation. Benjie Liu helped in validation and supervision.

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