Science and Technology for Energy Transition 77, 3 (2022)

https://doi.org/10.2516/stet/2022002

Selected Papers from 7th International Symposium on Hydrogen Energy, Renewable Energy and Materials (HEREM), 2021
Mohan Lal Kolhe (Guest Editor)

Available online at: stet-review.org

REGULAR ARTICLE OPEN ACCESS

Industrial characteristics of renewable energy and spatial aggregation correlations in Beijing–Tianjin–Hebei

Xiaotong Wu[1,2,a], Yang Zhou[1,a,*], Changchun Cheng[1], and Shiliang Yang[1]

[1] Business School, Hohai University, Nanjing, Jiangsu 211100, China
[2] College of Economics and Management, Nantong University, Jiangsu, Nantong 226019, China

Received: 20 October 2021 / Accepted: 2 February 2022

Abstract – Beijing–Tianjin–Hebei is a key development zone in China, and the renewable energy industry is particularly concerned. This paper aims to combine spatial information with renewable energy industry to reveal the spatial-temporal evolution characteristics of industry and its driving factors. It is found that the industries in Beijing, Tianjin and Hebei show an obvious agglomeration pattern, with the renewable energy industry in the Beijing–Tianjin–Hebei region showing Moran's I = 0.385579 during 2005–2010, Moran's I = 0.319463 during 2010–2015, and Moran's I = 0.329409 during 2015–2020. The global spatial autocorrelation analysis shows that the agglomeration level of the renewable energy industry in the Beijing–Tianjin–Hebei region has not increased, but the local spatial autocorrelation shows that the areas with higher transportation and business levels tend to be significantly agglomerated in space. Through the Moran index, it is found that the industry in Beijing–Tianjin–Hebei presents an obvious agglomeration pattern, and through the hotspot analysis, the industrial agglomeration is found mainly occurs in Beijing, Tianjin, Shijiazhuang and Zhangjiakou, which can be explained by the factor agglomeration effect brought by urbanization. However, we further calculated the location quotient, Herfindahl coefficient and Gini coefficient, and found significant regional differences in Beijing–Tianjin–Hebei region. For example, the unipolar agglomeration effect was weakening. Further three-phase space ellipse more vividly reveals the Beijing–Tianjin–Hebei region of renewable energy industry in the past 20 years continued to form the benign industrial expansion. Starting from the capital Beijing, the industry moved southwest, driving the development of renewable energy industry in Hebei and Tianjin, and promoting the coordinated development of the Beijing–Tianjin–Hebei economic circle.

Key words: Renewable industry, Industrial evolution, Spatial characteristics, Energy transition.

1 Introduction

Extreme global climate change caused by the excessive exploitation and use of traditional fossil fuels is becoming more and more intense, which has also aroused the attention and discussion of all sectors of society. As renewable energy can replace traditional energy and make up for energy shortage, it can reduce carbon dioxide emissions and environmental pollution caused by the use of traditional energy, which is of great help to improve the atmospheric environment (Lund, 2007; Panwar *et al.*, 2011). For this reason, the United Nations Intergovernmental Panel on Climate Change (IPCC) proposed the development of renewable energy to accelerate the world's energy transition to solve the current severe environmental problems. In this context, the renewable energy industry has also become a key emerging industry that affects the strategic security and competition of all countries (Johansson, 2013; Chalvatzis and Ioannidis, 2017). The Chinese government attaches great importance to the development of renewable energy industry to promote energy transformation, which is clearly reflected in the *Decision on Accelerating the Cultivation of Strategic Emerging Industries* issued by The State Council in 2010. Later, The State Council also drafted a special plan on taking the development of strategic emerging industries as the national macro development strategy. The development requirements and supporting policies for the development of renewable energy industry were emphasized.

From the perspective of research disciplines, most of the early studies on renewable energy industry discussed development issues from the perspective of industrial economics

*Corresponding author: zhouY1231@outlook.com
[a]Xiaotong Wu and Yang Zhou contributed equally to this paper.

and environmental economics. In recent years, with the participation of geography and science scholars, research results on the development of renewable energy industry from the perspectives of geography and science have begun to appear. For example, Tilleman (2011) takes wind energy and solar energy manufacturing clusters as an example and finds that clusters are affected by supported institutional logic, knowledge spillover, labor sharing, technological uncertainty and other factors. Similarly, Misak and Prokop (2016), who provide a detailed analysis of the current mature renewable energy technologies at a technical level, and in particular, wind power and solar energy utilisation as two technologies that provide guidance on how to reduce costs in the process of production and utilisation at scale. Guo and Shen (2015) use the panel model to analyze the factors influencing the location of renewable energy industrial clusters and draw a similar conclusion, and believe that renewable energy infrastructure construction, technological innovation level, government policy support and other factors are the most important. Bai *et al.* (2020) constructed a data model of the rising trend of renewable energy technology innovation in China's provinces during the period 1997–2015 and found that patent protection mechanisms had a non-negligible effect on the improvement of renewable energy technology innovation capacity in each province. Benedek *et al.* (2013) believe that renewable energy industrial cluster is actually an ecological cluster, a special form of cluster, because regional development, renewable energy and environmental variables are added to cluster, thus reflecting the concept of sustainable development. By establishing a regression model, Li *et al.* (2020) confirmed the positive correlation between industrial clusters and regional economic development and showed that urban residents' disposable income is a key factor in promoting regional economic development in both absolute and relative terms. Wu *et al.* (2020) studied the threshold effect and found that industrial agglomeration has a nonlinear impact on energy efficiency, which is mainly affected by the energy structure and the degree of market-oriented reform. Through the review of the existing research content of renewable energy industry, it can be found that the research mainly focuses on three aspects: the economic relevance of the development of renewable energy industry, the patent protection mechanism in the development process of renewable energy industry, and the spatial distribution evolution of the development of renewable energy industry.

The development of renewable energy industry can effectively drive the development of related industries, and has become an important force in China's economic and social development and strategic adjustment of economic structure (Hua *et al.*, 2016; Zhang *et al.*, 2017). In the era of globalization, the importance of the renewable energy industry is more prominent, developed countries generally regard the renewable energy industry as the lifeblood, and strive to build and maintain its competitive advantage (Amri, 2017; Zhou *et al.*, 2020). At present, China's renewable energy industry has a good momentum of development, especially in the wind power industry, photovoltaic power industry and biomass energy industry, but there are still high research and development and promotion costs that restrict the development of the industry (Xu *et al.*, 2019; Zhang *et al.*, 2017). Especially since the implementation of *China's 13th Five-Year Plan for Renewable Energy* in 2016, the coordinated development of Beijing–Tianjin–Hebei region is considered to play a role in promoting the production efficiency of the renewable energy industry, the replacement of traditional energy sources, and the improvement of ecological conditions (Zhang and Zheng, 2020). At the present stage, the Beijing–Tianjin–Hebei Metropolitan area is regarded as a strategic development area in China and has great research value. As the capital of China, Beijing, is not only the administrative center, but also the core of the economic development in northern China. It is a densely populated city with a permanent population of 21.89 million. As one of the earliest industrialized cities in China, the local government of Tianjin has been making energy transformation a major goal. Hebei province has a serious imbalance in industrial distribution, which is a typical area dominated by carbon intensive industries. Considering the unbalanced development of these regions, an in-depth study on the distribution pattern and evolution trend of the renewable energy industry in the Beijing–Tianjin–Hebei region can better analyze the policy effectiveness and provide reference for optimizing the spatial distribution of the regional renewable energy industry.

Although many scholars have analysed regional development differences and spatial agglomeration through the Industrial Agglomeration Index (EG), the locational entropy index and the global Moran's I method, there is still a lack of research data on the Beijing–Tianjin–Hebei region. This is because of the lack of timely data and the difficulty of interdisciplinary research. However, in recent years, studies on spatial point data, such as POI, have gradually increased (Qian *et al.*, 2021; Pan *et al.*, 2021; Sojahrood and Taleai, 2021). This is because combining spatial location data with multi-source statistical data can help obtaining richer "images" (Zhu *et al.*, 2021). For example, Bai *et al.* (2021), by mining the location information of smart grid patent, finally concluded that the trend of innovation evolution in China is not only related to the level of economic development, but also related to regional industrial culture and spatial characteristics. Although this kind of research is still in its infancy, its potential has been recognized by many scholars (Wu *et al.*, 2021). Therefore, this study uses spatial location data combined with the Industrial Agglomeration Index and other relevant evaluation methods through geographic visualisation analysis software. The analysis of the evolution of the spatial distribution and agglomeration of the renewable energy industry in Beijing, Tianjin and Hebei between 2000 and 2021 will be more intuitive and provide a reliable research basis for the future development of the renewable energy industry in this region to a certain extent.

2 Methodology

This study therefore uses the data obtained from the China's National Industrial and Commercial Database

Platform. Based on this data source, we classified the geographic information on the business registration of renewable energy enterprises into categories and used the open platform to obtain geographic coordinates to collate the raw spatial location data needed for the study. Moreover, the data on the natural endowment of renewable energy resources and the level of regional economic development required for the subsequent analysis were obtained from the *China Statistical Yearbook* from 2000 to 2021.

2.1 Spatial autocorrelation

This paper uses Moran's I index to test whether there is spatial dependence or spatial heterogeneity among cities in the Beijing–Tianjin–Hebei region, and analyzes the spatial correlation characteristics of the renewable energy industry in 14 cities in the region. Moran's index is divided into Global Moran's I and Local Moran's I. The former is a measure of spatial autocorrelation developed by Patrick Alfred Pierce Moran. The latter was proposed by Luc Anselin (1995).

The formula for the global Moran's I index is as follows:

$$\text{Moran's } I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\mathbf{W}_{ij}(Y_i-\bar{Y})(Y_J-\bar{Y})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}}. \quad (1)$$

Among which, $S^2=\frac{1}{n}\sum_{i=1}^{n}(Y_i-\bar{Y})$, $\bar{Y}=\frac{1}{n}\sum_{i=1}^{n}Y_i$, Moran's I is the global spatial autocorrelation index; $\mathbf{W}_{ij}$ is the element of spatial weight matrix; Y_i, Y_J respectively represent the productivity of renewable energy industry of i, j, city; n is the number of cities in the study area.

The formula of local Moran's I index is as follows:

$$\text{Moran's } I = \frac{(x_i-\bar{x})}{\sum_i (x_i-\bar{x})^2}\sum_j w_{ij}(x_i-\vec{x}). \quad (2)$$

2.2 Location quotient

Location Quotient (LQ) is an indicator of regional concentration of production, also known as specialization rate. It was first proposed by American economist Haggett and used in Location analysis to measure the spatial distribution of factors in a region and reflect the degree of specialization and industrial agglomeration of an industry sector. Kim (1990) conducted an empirical study made on the identification of industrial clusters along the Yellow Sea coast of China by using location quotient, and the results show that location quotient is reasonable and feasible in China.

The location business method mainly measures the degree of industrial agglomeration by calculating the LQ coefficient to judge the existence of industrial cluster. LQ coefficient refers to the ratio of the share of an industry in a smaller region to the share of the industry in a larger region. The formula for calculating LQ coefficient is:

$$LQ_i = \frac{E_{ij}/E_i}{E_{kj}/E_k}. \quad (3)$$

Among which, E_{ij} refers to the total output value of industry j in the smaller region i; E_i refers to the total output value in the region i; E_k refers to the total output value of country or region k. In the formula, the total output value can be selected as industrial gross output value, added value, number of enterprises, sales revenue, number of employees and other indicators. In this paper, the total industrial output value above scale is selected.

When the LQ coefficient is greater than 1, it indicates that the industry in the region has the advantage of specialization. When the LQ coefficient is greater than 1.2, it indicates that the region has a high level of specialization. However, the location business law can only reflect the degree of industrial agglomeration, but cannot identify the degree of linkages among related industries in industrial clusters. Therefore, it is necessary to use other methods to identify renewable energy industrial clusters.

2.3 Herfindahl–Hirschman Index

The Herfindahl–Hirschman Index (HHI) is a composite Index that measures industrial concentration. It refers to the square sum of the percentage of total revenue or total assets taken by all market competitors in an industry, which is used to measure the change of market share, namely the dispersion of the scale of firms in the market (Calkins, 1983). The closer its value is to 0, the lower the regional industrial concentration is; conversely, the closer it is to 1, the higher the concentration is. Its calculation formula is as follows:

$$H = \sum_{i=1}^{n} t_i^2. \quad (4)$$

For the calculation of the Gini coefficient of the Beijing–Tianjin–Hebei renewable energy industry, H is the Herfindahl–Hirschman Index; n refers to the city numbers; t_i $(i = 1, 2, 3 \ldots n)$ is the percentage of the total revenue of the renewable energy industry in the Beijing–Tianjin–Hebei region accounted for by the t-ranking city.

2.4 Space Gini coefficient

Lorenz created the Lorenz Curve, which explains the average degree of social distribution, when he studied the income distribution of residents. According to Lorenz curve, the Gini coefficient is used to calculate the fairness degree of income distribution. Using the principles and methods of Lorenz curve and Gini coefficient, Krugman (1986) constructed the spatial Gini coefficient to measure the equilibrium degree of spatial distribution of industries, and studied the degree of manufacturing agglomeration in the United States. The formula is as follows:

$$G = 1 + \frac{1}{n} - \frac{1}{n^2\bar{Y}}(y_1 + 2y_2 + 3y_3 + \cdots + ny_n), \quad (5)$$

where, G is Gini coefficient; n is the number of cities; $\bar{Y}$ is the mean value of total income of renewable energy industry in cities in Beijing, Tianjin and Hebei in a specific period; y_i $(i = 1, 2, 3 \ldots n)$ is the total revenue of the

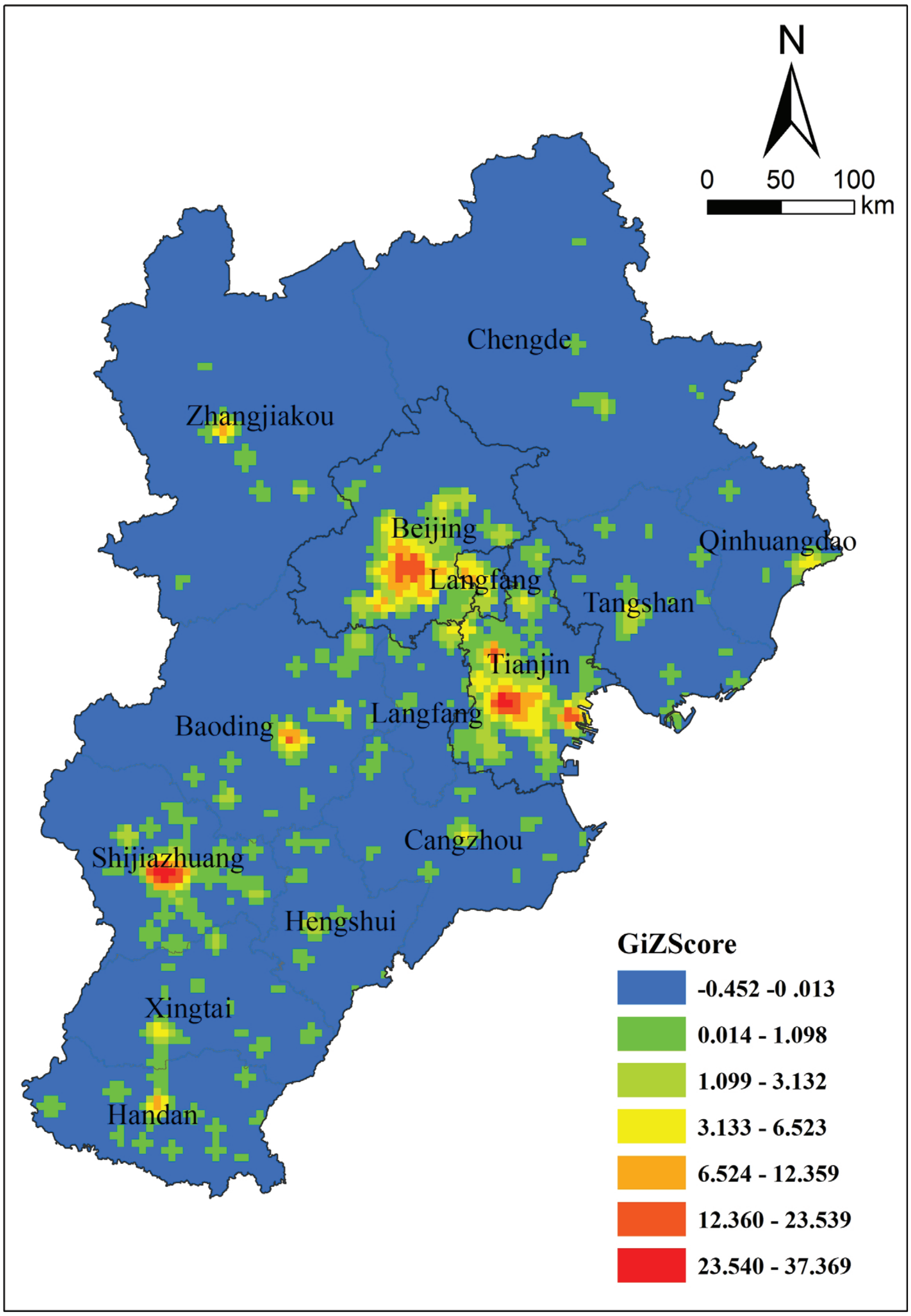


Fig. 1. Spatial distribution.

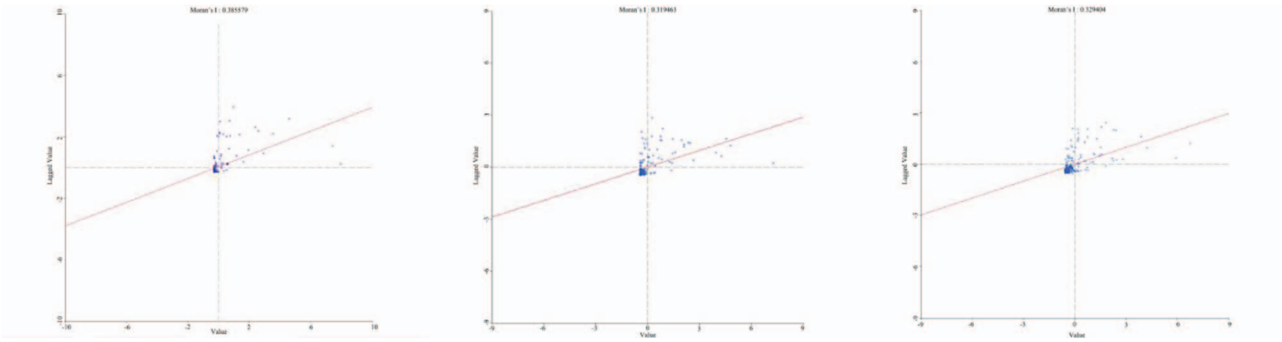
renewable energy industry in the ith city in the Beijing–Tianjin–Hebei region during the same period.

2.5 EG Index

EG index is to solve the distortion of spatial Gini index. Combined with Herfindahl (H), Ellison and Glaeser (1997) proposed a new agglomeration index to measure the degree of industrial agglomeration. It is an effective method to reflect the renewable energy industry in the Beijing–Tianjin–Hebei region, and can measure the agglomeration and dispersion trend of the renewable energy industry in the Beijing–Tianjin–Hebei region within a certain period of time. The calculation formula (γ^{EG}) is as follows:

$$\gamma^{\mathrm{EG}} = \frac{G - \left(1 - \sum_i x_i^2\right)H}{\left(1 - \sum_i x_i^2\right)H(1-H)}. \tag{6}$$

Among which, G is spatial Gini coefficient; H is Herfindahl index; i and j represent regions, u is the mean value



2005-2010 2010-2015 2015-2020

Fig. 2. Moran scatter chart.

of x_i; x is the area proportion of region i or j; n is the number of regions.

2.6 Standard Deviational Ellipse

Standard Deviational Ellipse (SDE) method is a classical method to analyze spatial direction and distribution characteristics. The result is ellipse distribution map. The size of ellipse reflects the concentration degree of the overall elements of spatial pattern, the short axis represents the distribution range of data, and the long axis reflects the dominant direction of spatial distribution (Yuill, 1971). SDE can summarize the central trend, discrete trend and direction trend of geographical elements, so as to obtain the spatial characteristics of elements. The calculation formula of this method is as follows:

$$\mathrm{SDE}_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}}, \quad (7)$$

$$\mathrm{SDE}_y = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n}}. \quad (8)$$

Among which, SDE_x and SDE_y represent the center of the calculated ellipse, x_i and y_i are the spatial location of element i, $\bar{x}$ and $\bar{y}$ represent the center of arithmetic mean (*i.e.* the center of ellipse), n represents the total number of elements analyzed.

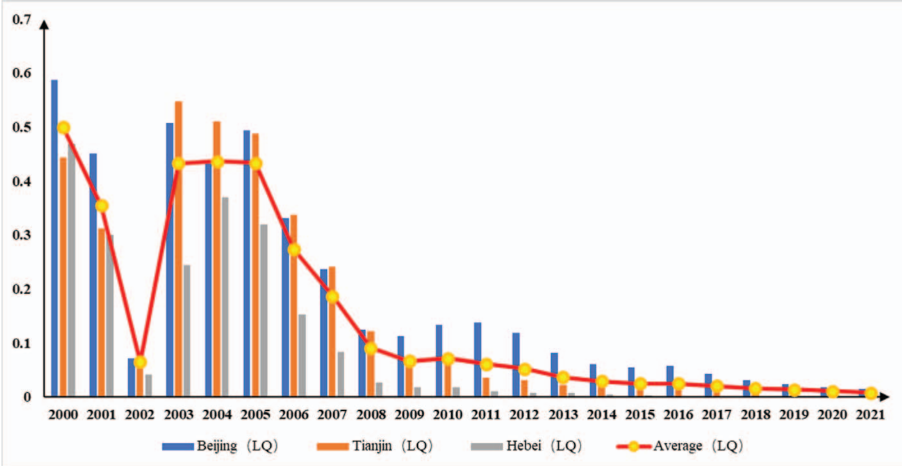
3 Results

The renewable energy industry is an intelligence-intensive emerging industry with strong professionalism and technology, and its spatial agglomeration is affected by various economic and non-economic factors (Sigurdson, 2004). As China's important administrative and economic center, as well as an important commercial and cultural center, Beijing has irreplaceable advantages in promoting the development of renewable energy industry (Li *et al.*, 2015).

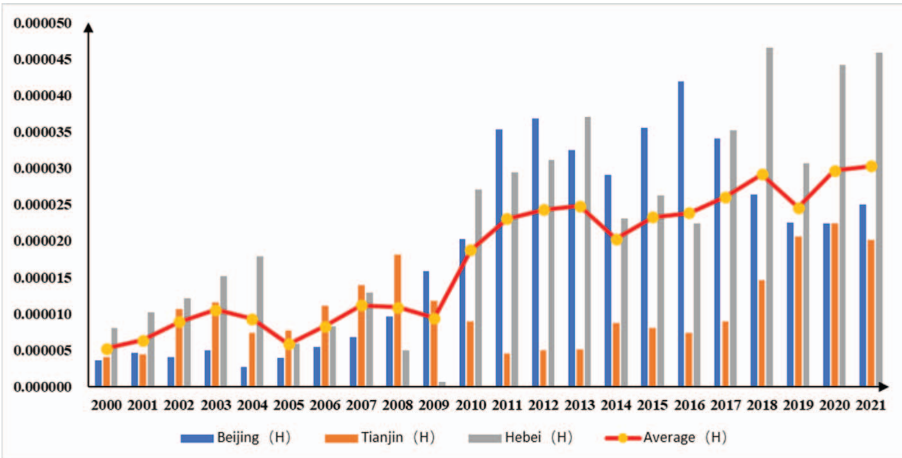
As shown in Figure 1, the core density of the Beijing–Tianjin–Hebei region is the highest in the central urban area of Beijing–Tianjin–Hebei compared with other areas of the region. The highly concentrated distribution areas of renewable energy industry points in Beijing–Tianjin–Hebei are mainly concentrated in the center of Beijing, the center of Tianjin and the central urban area of Shijiazhuang, basically along the direction of "northeast to southwest", and the spatial distribution direction is obvious. The spatial distribution of the renewable energy industry has initially formed a polycentric morphological distribution characteristics, and presents a polycentric circle structure system, although there is an obvious primary and secondary order. The renewable energy industry centers in the peripheral cities are discrete, mainly distributed around the administrative center with a small scale and limited space coverage. The major renewable energy industry centers consist of the urban areas of Beijing. The secondary renewable energy industry centers are mainly distributed in the central urban area of Tianjin, Tianjin Binhai New Area, Shijiazhuang main urban area, *Zhangjiakou High-Tech Pioneer Park* area and *Handan Industrial Park*, among which Tianjin forms a dual center structure. It can be seen that the location of renewable energy industry in the central urban area will be more supportive in attracting talents, introducing capital and enhancing intra-industry cooperation, so the renewable energy industry is more likely to produce agglomeration effect in such areas (Begg, 1999).

Since the period from 2000 to 2005 belongs to the initial stage of the development of renewable energy industry in the Beijing–Tianjin–Hebei region, the data collected by this study indicates that the number of renewable energy enterprises during this period is not enough to reflect the regional industrial spatial evolution law. Therefore, three time periods (2005–2010, 2010–2015 and 2015–2020) are selected to analyze the spatial agglomeration of the renewable energy industry in cities in Beijing–Tianjin–Hebei region, and the results are as follows (see Fig. 2).

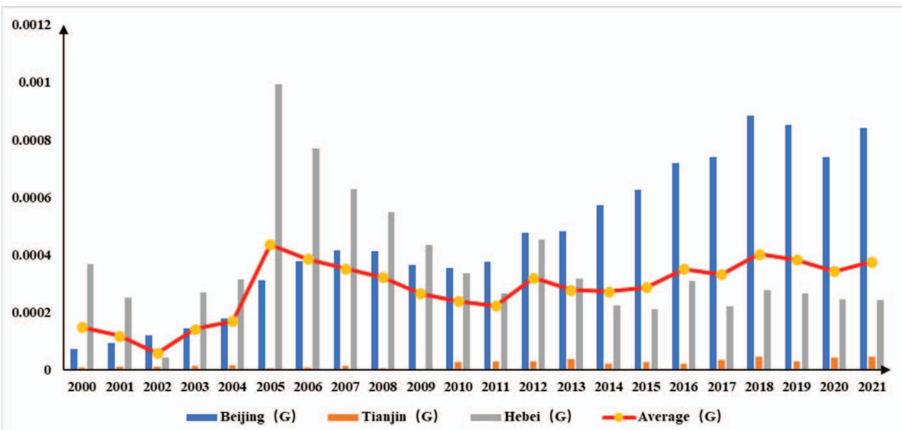
According to the global autocorrelation analysis results in Figure 2, the spatial agglomeration characteristics of renewable energy industry in Beijing–Tianjin–Hebei region are obvious, showing a trend of gradual decline from the center to the periphery, and there is an obvious diffusion effect. Moran's $I = 0.385579$ from 2005 to 2010, 0.319463



(a)



(b)



(c)

Fig. 3. Agglomeration of renewable energy industry in Beijing–Tianjin–Hebei. (a) Location Quotient (LQ). (b) Herfindahl coefficient (H). (c) Spatial Gini coefficient (G).

from 2010 to 2015, and 0.329409 from 2015 to 2020. This means that the areas with higher development level of renewable energy industry in the Beijing–Tianjin–Hebei region tend to cluster significantly in space. This spatial distribution remained unchanged from 2005 to 2020.

In order to further investigate the spatial aggregation changes of renewable energy industry in the Beijing–Tianjin–Hebei region, the analysis of Figure 2 shows that most cities in the Beijing–Tianjin–Hebei region are distributed in the first and third quadrants, namely, the renewable energy industry in each city has a strong spatial autocorrelation. Specifically, the urban areas of Beijing and Tianjin are located in the first quadrant within 15 years, forming a stable high-high spatial positive correlation aggregation area, which has a strong positive radiation and driving effect on the adjacent cities, and promotes the development of renewable energy industry together with the surrounding cities. Chengde, Qinhuangdao, Hengshui and Cangzhou were all in the third quadrant within 15 years, forming a low-low spatial autocorrelation cluster, which played a negative radiative driving role to neighboring cities. Zhangjiakou, Handan and Baoding are mainly in the second quadrant, which have different attribute values from neighboring cities and have a weak impact on surrounding cities. Therefore, it is necessary to pay attention to the introduction of capital and talents in the development process of renewable energy industry and promote the transformation of technological achievements. Xingtai, Tangshan and Langfang have shifted from the third quadrant to the second quadrant, namely low-high cluster areas, failing to effectively accept the impetus of the development of renewable energy industry in surrounding cities. In the past 15 years, Shijiazhuang has been in the fourth quadrant, that is, the high-low aggregation area, which has a relatively weak radiating and driving effect on the green innovation development of surrounding cities. However, by 2020, the development level of renewable energy industry in surrounding areas has been improved to some extent. Based on the above analysis, it can be seen that the renewable energy industry of 14 cities in the Beijing–Tianjin–Hebei region has a certain spatial autocorrelation, especially the high-high clustering type centered on Beijing and Tianjin and the low-low clustering type centered on Chengde, Qinhuangdao, Hengshui and Cangzhou are increasingly significant and tend to be stable. In general, the spatial relationship between the development of renewable energy industry in cities in the Beijing–Tianjin–Hebei region has been stable from 2005 to 2020, and the agglomeration effect has not been significantly enhanced. With the strengthening of communication among cities, the radiation scope of High-High cluster of renewable energy industry centered in Beijing and Tianjin has been expanded.

As shown in the Figure 3, from 2000 to 2021, the maximum value of LQ of Beijing's renewable energy industry reached 0.59 in 2000, and dropped to the minimum value of 0.015 in 2021 by the time this study is carried out. In addition, the H and G coefficients are not high, indicating that the development trend of Beijing's renewable energy industry cluster is relatively slow and the agglomeration phenomenon has not been further strengthened. Relying on the R&D centers with strong scientific research ability, Beijing has a certain advantage in the field of renewable energy, and has initially formed an industrial cluster where enterprises, R&D institutions and industrial alliances promote each other. However, due to the lack of other resources, the industrial clusters formed today still need to be broken through in terms of technological innovation. The LQ index of Tianjin began to decline from 2003, and the LQ index of Tianjin's renewable energy industry dropped to the lowest 0.009 in 2021. The current concentration is less obvious than in other industries. Tianjin Binhai New Area and High-Tech Zone have renewable energy industrial parks, but the renewable energy industry is beginning to take shape, the degree of product differentiation is not high, and the supporting public services are not perfect. The LQ index of Hebei is lower than that of Beijing and Tianjin, and the spatial distribution of renewable energy industry in the region is more dispersed due to the large area of Hebei province.

The location quotient (LQ) of Beijing–Tianjin–Hebei region showed a decreasing trend. The Herfindahl coefficient (H) of Beijing showed an unstable upward trend from 2000 to 2015, and began to decline slowly from 2015 to 2020. Tianjin and Hebei showed a relatively stable upward trend. The spatial Gini coefficient (G) of Beijing is stable, that of Tianjin is on the rise, and that of Hebei is on the decline. The spatial agglomeration index (EG) of the Beijing–Tianjin–Hebei region is not high in recent years (Table 1),

Table 1. EG Index results.

EG index	Beijing–Tianjin–Hebei region
2000	0.001347
2001	0.001302
2002	0.001257
2003	0.001211
2004	0.001166
2005	0.001317
2006	0.001178
2007	0.001053
2008	0.000923
2009	0.000744
2010	0.000703
2011	0.000616
2012	0.000912
2013	0.000901
2014	0.000802
2015	0.000741
2016	0.000624
2017	0.000579
2018	0.000534
2019	0.000489
2020	0.000444

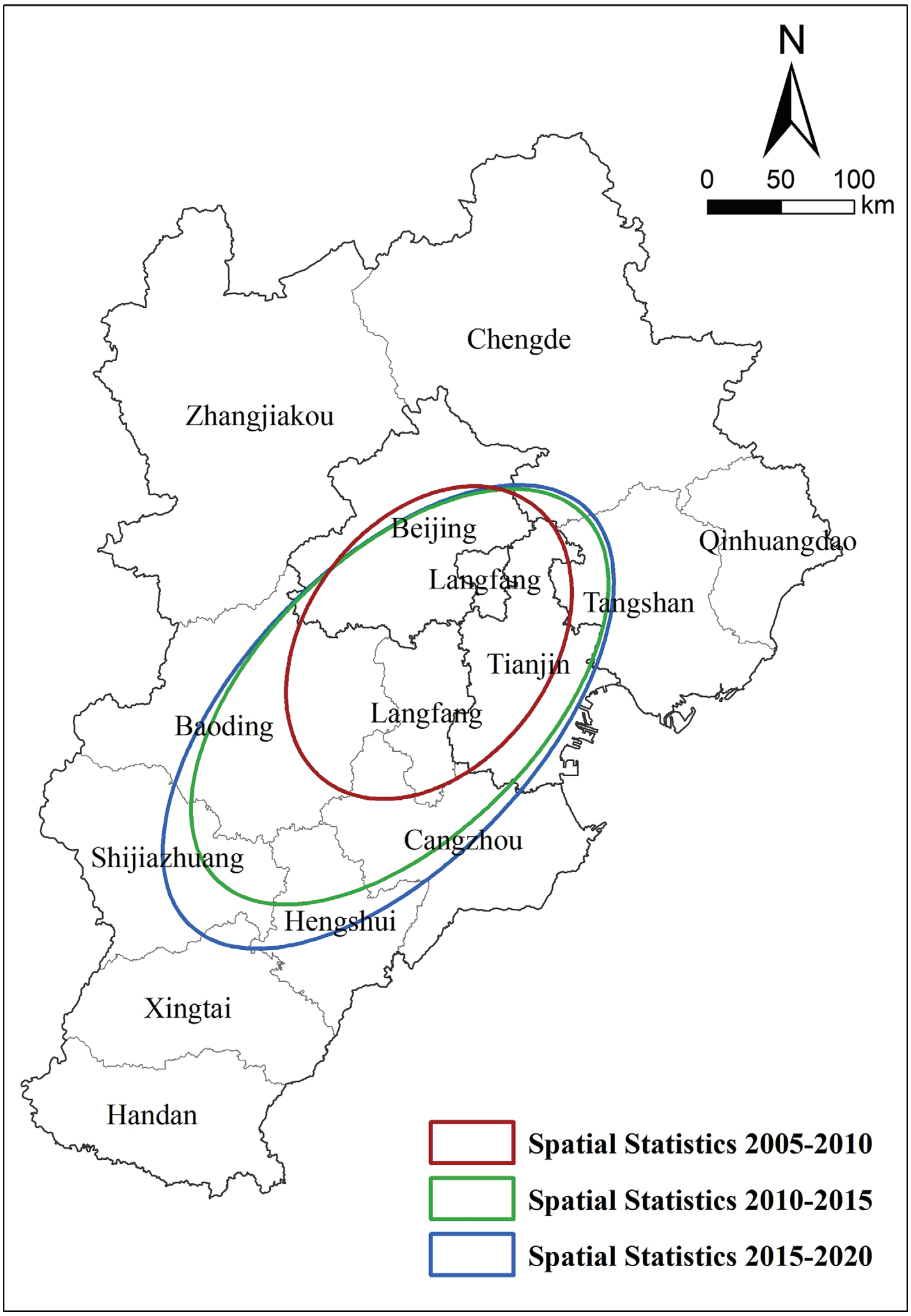


Fig. 4. SDE movement of Beijing–Tianjin–Hebei Renewable Energy Industry.

and the renewable energy industry in the Beijing–Tianjin–Hebei region is a low-agglomeration industry, indicating that the renewable energy industry has not formed industrial clusters in the Beijing–Tianjin–Hebei region. For LQ, H and G coefficients, the detailed index values can be seen in the Appendix.

The distribution of the renewable energy industry in the three stages was superimposed on the administrative region of Beijing–Tianjin–Hebei, and the orientation of the renewable energy industry in the spatial pattern was explored by using the standard deviation ellipse analysis tool. The results of the ellipse analysis of standard deviation in the three periods of 2005–2010, 2010–2015 and 2015–2020 are shown in Figure 4. Red is 2005–2010, green is 2010–2015, and blue is 2015–2020.

Through standard deviation ellipse analysis, it can be seen that the spatial distribution of the renewable energy industry in the three stages presents an obvious southwest extension. It reflects that the spatial development of the renewable energy industry in the three stages of Beijing–Tianjin–Hebei mainly extends upward in the south and north, which is consistent with China's current policy of vigorously developing Xiongan as the sub-center of Beijing. Xiongan District is located in the southwest of Beijing. The standard deviation ellipse from 2015 to 2020 mainly covers Beijing, Langfang, Tianjin, Cangzhou, Baoding, Hengshui, Shijiazhuang and part of Xingtai, Tangshan and Chengde. The standard deviation ellipse from 2005 to 2010 mainly covers Beijing, Langfang and Tianjin. The comparative analysis results show that the long axis and the short axis of the standard deviation ellipse from 2015 to 2020 are larger than the first two periods, indicating that the spatial scope of the renewable energy industry in the Beijing–Tianjin–Hebei region is expanding, which corresponds to the conclusion of the spatial autocorrelation analysis.

4 Conclusion

With the continuous development of China's economy, the supply and demand of energy is increasing. At the same time, the problem of environmental governance and protection cannot be ignored. Therefore, it is necessary to develop the renewable energy industry. In this context, it is of theoretical and practical significance to study the agglomeration effect and spatial evolution of the regional renewable energy industry. This paper uses Industrial geographical data of 14 cities in the Beijing–Tianjin–Hebei region from 2000 to 2021 to analyze the spatial development changes of renewable energy industry by ArcGis software. The results show that:

1. The Beijing–Tianjin–Hebei renewable energy industry is distributed in the direction of "northeast to southwest", presenting a system with one main center and several secondary centers. And highly concentrated area center mainly concentrated in the urban areas of Beijing, Tianjin and Shijiazhuang city. It shows that the location of renewable energy industry in the central city will play more support in attracting talents, introducing capital and enhancing intra-industry cooperation. Therefore, renewable energy industry is more likely to produce agglomeration effect in such areas.
2. Moran's $I = 0.385579$ during 2005–2010, 0.319463 during 2010–2015, and 0.329409 during 2015–2020 for the renewable energy industry in Beijing–Tianjin–Hebei region. The global spatial autocorrelation analysis shows that the agglomeration level of renewable energy industry in Beijing–Tianjin–Hebei region has not increased, but the local spatial autocorrelation shows that the areas with higher traffic and commercial level tend to be significantly concentrated in space. In general, the agglomeration effect of renewable energy industry in cities in the Beijing–Tianjin–Hebei region has not been significantly enhanced from 2005 to 2020, and only the H-H cluster of renewable energy industry centered in Beijing and Tianjin has a diffusion effect on the surrounding areas.
3. The location quotient (LQ), Herfindahl coefficient (H), Spatial Gini coefficient (G) and spatial agglomeration index (EG) of the Beijing–Tianjin–Hebei region all indicate that the renewable energy industry is a low-agglomeration industry in the Beijing–Tianjin–Hebei region. It can be considered that the renewable energy industry has not formed industrial clusters in the Beijing–Tianjin–Hebei region.
4. According to the standard deviation ellipse analysis, the long axis and short axis of the standard deviation ellipse extend to the southwest with the passage of time from 2005 to 2020, indicating that the spatial scope of the renewable energy industry in the Beijing–Tianjin–Hebei region is constantly expanding, and extending upward to the south and north. This result corresponds to the conclusion of the spatial autocorrelation analysis.

This paper draws these conclusions from an empirical study of the renewable energy industry in the Beijing–Tianjin–Hebei region, focusing on the distribution of regional renewable energy infrastructure, renewable energy resource endowments, regional economic development levels, local government policy support, and the spatial evolution of the renewable energy industry in the same region over time, as well as the different locational influences that are more likely to form renewable energy industry clusters with policy support. There are, of course, some limitations to this paper. In doing a panel data analysis of the location of renewable energy industry clusters, the choice of proxy variables for each factor may affect the measurement results, so the proxy variables need to be further optimised, and because the data is a short panel, it is not possible to use dynamic panel data analysis to explore the path dependence of regional renewable energy industry clusters in depth, which requires a long-term continuous research on the development of renewable energy clusters.

References

Amri F. (2017) Intercourse across economic growth, trade and renewable energy consumption in developing and developed countries, *Renew. Sust. Energ. Rev.* **69**, 527–534.

Anselin L. (1995) Local indicators of spatial association – LISA, *Geogr. Anal.* **27**, 2, 93–115.

Bai C., Feng C., Du K., Wang Y., Gong Y. (2020) Understanding spatial-temporal evolution of renewable energy technology innovation in China: Evidence from convergence analysis, *Energy Policy* **143**, 111570.

Bai Y, Chou L, Zhang W (2021) Industrial innovation characteristics and spatial differentiation of smart grid technology in China based on patent mining, *J. Energy Storage* **43**, 103289.

Begg I. (1999) Cities and competitiveness. *Urban Studies* **36**, 5–6, 795–809.

Benedek J., Cristea M., Bartók B. (2013) Regional development and establishment of renewable energy clusters in North-West Region of Romania, *Environ. Eng. Manag. J.* **12**, 2, 237–244.

Calkins S. (1983) The new merger guidelines and the Herfindahl-Hirschman Index, *Calif. Law Rev.* **71**, 402.

Chalvatzis K.J., Ioannidis A. (2017) Energy supply security in the EU: Benchmarking diversity and dependence of primary energy, *Appl. Ener.* **207**, 465–476.

Ellison G., Glaeser E.L. (1997) Geographic concentration in US manufacturing industries: a dartboard approach, *J. Polit. Econ.* **105**, 5, 889–927.

Guo L.W., Shen M.H. (2015) Study on location selection factors of renewable energy industrial cluster, *Learn. Pract.* **2**, 31–41.

Hua Y., Oliphant M., Hu E.J. (2016) Development of renewable energy in Australia and China: A comparison of policies and status, *Renew. Ener.* **85**, 1044–1051.

Johansson B. (2013) Security aspects of future renewable energy systems – A short overview, *Energy* **61**, 598–605.

Kim W.B. (1990) The future of coastal development in the Yellow Sea Rimlands, *J. Northeast Asian Stud.* **9**, 4, 53–70.

Krugman P.R. (Ed.) (1986) *Strategic trade policy and the new international economics*, MIT Press.

Li H., Guo S., Cui L., Yan J., Liu J., Wang B. (2015) Review of renewable energy industry in Beijing: Development status, obstacles and proposals, *Renew. Sust. Energ. Rev.* **43**, 711–725.

Li H., Zhao Y., Wang S., Liu Y. (2020) Spatial-temporal characteristics and drivers of the regional residential CO_2 emissions in China during 2000–2017, *J. Clean. Prod.* **276**, 124116.

Lund H. (2007) Renewable energy strategies for sustainable development, *energy* **32**, 6, 912–919.

Misak S., Prokop L. (2016) *Operation characteristics of renewable energy sources*, Springer.

Pan J., Huang W., Li X., Li R. (2021) Spatial distribution and regional accessibility measurement of financial services in china, *Arab. J. Geosci.* **14**, 17, 1–11.

Panwar N.L., Kaushik S.C., Kothari S. (2011) Role of renewable energy sources in environmental protection: A review, *Renew. Sust. Energ. Rev.* **15**, 3, 1513–1524.

Qian X., Bai Y., Huang W., Dai J., Li X., Wang Y. (2021) Fuzzy technique application in selecting photovoltaic energy and solar thermal energy production in belt and road countries, *J. Energy Storage* **41**, 102865.

Sigurdson J. (2004) *Regional innovation systems (RIS) in China*, European Institute of Japanese Studies.

Sojahrood Z.B., Taleai M. (2021) A POI group recommendation method in location-based social networks based on user influence, *Expert Syst. Appl.* **171**, 114593.

Tilleman S.G. (2011) *Institutional logics and regional cluster emergence: evidence from the wind and so-lax energy industries [D 1]*, University of Montana.

Wu C.Q., Zheng K.Y., Gao M.L. (2020) *Nonlinear effects of industrial synergy agglomeration on total factor energy efficiency in the Yangtze River Economic Belt*, Journal of Wuhan University of Technology Social Sciences.

Wu M., Pei T., Wang W., Guo S., Song C., Chen J., Zhou C. (2021) Roles of locational factors in the rise and fall of restaurants: A case study of Beijing with POI data, *Cities* **113**, 103185.

Xu X., Wei Z., Ji Q., Wang C., Gao G. (2019) Global renewable energy development: Influencing factors, trend predictions and countermeasures, *Resour. Policy* **63**, 101470.

Yuill R.S. (1971) The standard deviational ellipse; an updated tool for spatial description, *Geogr. Ann. B: Hum. Geogr.* **53**, 1, 28–39.

Zhang D., Wang J., Lin Y., Si Y., Huang C., Yang J., Li W. (2017) Present situation and future prospect of renewable energy in China, *Renew. Sust. Energ. Rev.* **76**, 865–871.

Zhang J., Zheng Y. (2020) The flexibility pathways for integrating renewable energy into China's coal dominated power system: The case of Beijing-Tianjin-Hebei Region, *J. Clean. Prod.* **245**, 118925.

Zhou X., Song M., Cui L. (2020) Driving force for China's economic development under Industry 4.0 and circular economy: Technological innovation or structural change? *J. Clean. Prod.* **271**, 122680.

Zhu X., Dai J., Wei H., Yang D., Huang W., Yu Z. (2021) *Application of the fuzzy optimal model in the selection of the startup hub*, Discrete Dynamics in Nature and Society.

Appendix

Table A1. Beijing–Tianjin–Hebei renewable energy industry agglomeration indexes.

Region	Year	Location Quotient Coefficient	Herfindahl Coefficient	Spatial Gini coefficient (G)
Beijing	2000	0.587668209	0.000004	0.000072
	2001	0.451851556	0.000005	0.000095
	2002	0.071042557	0.000004	0.000121
	2003	0.507745332	0.000005	0.000143
	2004	0.43200143	0.000003	0.000179
	2005	0.494686039	0.000004	0.000312
	2006	0.331183684	0.000005	0.000379
	2007	0.23715677	0.000007	0.000416
	2008	0.124846846	0.000010	0.000414
	2009	0.112832296	0.000016	0.000366
	2010	0.133204794	0.000020	0.000355
	2011	0.138428511	0.000035	0.000375
	2012	0.118578385	0.000037	0.000476
	2013	0.08096762	0.000032	0.000481
	2014	0.061117494	0.000029	0.000572
	2015	0.054849033	0.000036	0.000626
	2016	0.057460892	0.000042	0.000719
	2017	0.043879226	0.000034	0.000740
	2018	0.030819933	0.000026	0.000884
	2019	0.0240291	0.000022	0.000851
	2020	0.018805383	0.000022	0.000740
	2021	0.01514878	0.000025	0.000840
Tianjin	2000	0.443565251	0.000004	0.000008
	2001	0.311794821	0.000004	0.000010
	2002	0.082031733	0.000011	0.000012
	2003	0.547496858	0.000012	0.000015
	2004	0.509636058	0.000007	0.000018
	2005	0.488107368	0.000008	0.000006
	2006	0.337406538	0.000011	0.000008
	2007	0.241269802	0.000014	0.000013
	2008	0.122119638	0.000018	0.000005
	2009	0.069040282	0.000012	0.000001
	2010	0.062730148	0.000009	0.000027
	2011	0.03526251	0.000005	0.000029
	2012	0.030808298	0.000005	0.000031
	2013	0.022642243	0.000005	0.000037
	2014	0.023755796	0.000009	0.000023
	2015	0.018559216	0.000008	0.000026
	2016	0.017074478	0.000007	0.000022
	2017	0.015960925	0.000009	0.000035
	2018	0.01633211	0.000015	0.000047
	2019	0.01633211	0.000021	0.000031
	2020	0.013362635	0.000022	0.000044
	2021	0.009650792	0.000020	0.000046

(Continued on next page)

Table A1. (Continued)

Region	Year	Location Quotient Coefficient	Herfindahl Coefficient	Spatial Gini coefficient (G)
Hebei	2000	0.469603574	0.000037	0.000369
	2001	0.300333891	0.000033	0.000250
	2002	0.041572738	0.000022	0.000042
	2003	0.244644553	0.000019	0.000269
	2004	0.369751297	0.000032	0.000313
	2005	0.319630893	0.000027	0.000993
	2006	0.153339942	0.000019	0.000769
	2007	0.082886455	0.000013	0.000628
	2008	0.026420058	0.000007	0.000548
	2009	0.018260922	0.000007	0.000434
	2010	0.018390432	0.000006	0.000335
	2011	0.011137867	0.000004	0.000268
	2012	0.008288646	0.000003	0.000453
	2013	0.007252565	0.000004	0.000317
	2014	0.004662363	0.000003	0.000223
	2015	0.002719712	0.000002	0.000211
	2016	0.001813141	0.000002	0.000311
	2017	0.002201671	0.000001	0.000222
	2018	0.001554121	0.000001	0.000277
	2019	0.000906571	0.000001	0.000266
	2020	0.00051804	0.000001	0.000245
	2021	0.00038853	0.000001	0.000244