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Regional renewable energy development in China: A multidimensional assessment

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A R T I C L E I N F O

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A B S T R A C T

Renewable energy (RE) is strategically important to achieve sustainability. Its development in China, however, is clearly imbalanced across regions. The uneven distribution of natural resources, financial resources and other factors across this country has brought serious challenges to the policymakers. It is thus important to give a comprehensive evaluation of China's regional RE development. To do so, this paper introduces a multidimensional approach and establishes a quantitative evaluation framework. Based on the existing literature, five dimensions of factors have been chosen for the framwork: economic foundation, institutions, technological development potential, energy security and environmental protection, and current status of the RE sector. A dynamic principal component analysis technique is applied to data from 29 provinces between 2008 and 2014. The results demonstrate large variations in RE development across provinces in China. More economically developed regions, such as Beijing, Shanghai, and Guangdong, have maintained a higher ranking and have clear advantages in almost all dimensions. Policy implications and recommendations for more balanced development across China are drawn from the empirical results. This approach can also be extended to investigate similar issues in other countries.

Author contributions

Ying Wang: data collection, modelling and analysis, and writing - Original Draft. Dayong Zhang: conceptualization, methodology, resources, project administration, funding acquisition, writing – original draft, review & editing. Qiang Ji: resources, Validation, funding acquisition, writing - review & editing. Xunpeng Shi: methodology, literature review, interpretation, funding acquisition, and writing - review & editng.

1. Introduction

Developing renewable energy (RE)[1] has become a key solution to cope with climate change and the worsening environment in China. RE has also been adopted as a crucial step forward in most countries in the world, and as many as 176 countries have clear RE targets [1]. China, as

Abbreviations: RE, renewable energy; GHG, greenhouse gases; FYP, five-year plan; TCE, tons of standard coal equivalent; TPES, total primary energy supply; REL, Renewable Energy Law; GWh, gigawatt hours; 3 N, northern China; northwestern China, and northeastern China; GDP, gross domestic product; DPCA, dynamic principal component analysis; RECAI, renewable energy country attractiveness index; EKC, environmental Kuznets curve; OECD, Organization for Economic Cooperation and Development; ARDL, autoregressive distributed lag; FDI, foreign direct investment; BRICS countries, Brazil; Russia, India; China, and South Africa; NBS, National Bureau of Statistics of China; INEMS, Integrated National Energy Modelling System. RERII; Renewable Energy Responsible Investment Index. GCA, grey cluster analysis.

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[1] According to the US Energy Information Administration (www.eia.gov), renewable energy covers biomass, hydropower, geothermal, wind and solar. Among these energy forms, hydropower and traditional biomass are often excluded from RE policy discussions [3]. Solar and wind power are the main sources in the remaining part, and thus the main focus of relevant studies [4].

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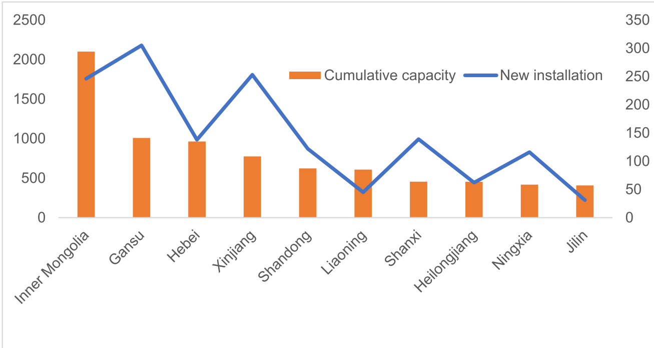

Fig. 1. Top 10 provinces in terms of cumulative wind generation capacity in 2014. Source: China National Energy Administration, 2015 (Unit: 10 MWh; cumulative capacity on the left axis and new installation on the right).

the largest developing economy and the biggest emitter of greenhouse gases (GHG), has actively participated in the global coalition and made ambitious commitments to control CO_2 emissions. For example, China has committed to reaching its peak CO_2 emissions by 2030 [2]. Developing its RE sector is one of the most important measures for achieving these goals. China's thirteenth five-year plan (FYP; 2016–2020) reinforces the strategic importance of developing RE as part of the country's energy supply. It provides general guidance for achieving 15% share in the energy supply for sources besides fossil fuels by 2020 and a 20% share by 2030 [5]. In 2015, the total supply of new and renewable energy in China reached 0.436 billion tons of standard coal equivalent (TCE), which accounts for 10.1% of the total primary energy supply (TPES). The RE sector has made significant technological progress, which makes RE development in China less internationally dependent and more economically viable. For example, the price of solar photovoltaic modules fell over 60% during the twelfth FYP period [6]. The policy system has also substantially improved. Following the launch of the Renewable Energy Law (REL) in 2005, a systemic policy mix to support RE development, including an RE pricing system, financial support, and quality control, has been established.

Despite these achievements, RE development in China faces many challenges and constraints. For example, China has large-scale wind curtailments. Luo et al. [7] show that the rate of wind curtailment ranges up to 21.79% (in Jilin province), which corresponds to 1.572 GWh. The curtailment rate in Inner Mongolia, the province with the largest wind power capacity, is 15.22%, or 6.389 GWh. Similar issues can also be found in solar power [8]. The curtailments can generate large economic loss and power waste, which hinder further and more efficient RE development.

The curtailment is largely due to a lack of coordination among generation, transmission, and dispatch. As RE development is complicated by disparate factors, it requires a multidimensional evaluation. Luo et al. [7], for example, point out that power generation development is not in line with consumption markets. Moreover, large RE projects are often costly to construct, and the costs of developing RE are higher than those for traditional fossil fuel energy, which makes RE development both sensitive and vulnerable, to changes in policy support and subsidies. Zhang et al. [9] show clear evidence that an overinvestment problem exists in China's RE sector, especially in wind energy. Inappropriate policy support or an imbalanced system can cause unhealthy RE development.

Another major issue, which has often been ignored in the literature, concerns regional imbalances in RE development in China, especially the mismatch between resource endowments and demand. Being a vast country, China has significant regional variations in terms of natural resource endowments and economic development. For example, in wind energy (Fig. 1), the top 10 provinces for cumulative wind generation capacity are all in the three northern (3 N) regions (northern China, northwestern China, and northeastern China).

Regional imbalance in RE development can also be seen in other dimensions, such as economic development, employment, and environmental pressure [10]. As mentioned earlier, China has a mismatch between energy demand and supply. For example, Guangdong province, which produces the country's largest GDP (7282.1 billion RMB, or around 1.151 trillion USD [11]), also has the largest electricity deficit. Its consumption of electricity is 531.07 GWh, whereas its production of electricity is only 403.5 GWh—a deficit of 127.57 GWh [12]. The province with the largest industrial investment in energy, however, is Xinjiang, which is located more than 4000 km away from Guangdong. Institutional development and policy support also vary across provinces—for example, the pilot emission trading markets, which give firms in those regions more incentives to develop renewable energy. Although a national carbon market was announced in December 2017 [13], the regional imbalance remains.

The problem in RE development is more complicated when we consider upstream RE industries. Using the Chinese Industrial Enterprises Database, which covers information on over 95% of Chinese industrial output, Shi et al. [14] show that the distribution of renewable energy firms (including both upstream and downstream enterprises) is more concentrated in the eastern coastal regions, such as Shandong and Jiangsu provinces.

These regional imbalances and associated issues can cause serious problems for RE development and are among the main reasons for curtailments. Given the strategically important position of RE development and the aforementioned challenges and imbalances, a comprehensive evaluation of China's regional RE development is needed. While RE development is determined by resource endowment to some extent, a comprehensive assessment can help policymakers understand what intervention could be initiated to further advance RE development.

We use a dynamic principal component analysis (DPCA) method to construct a multidimensional measure of RE development in China's provinces. The choice of dimensions and subdimensional factors, to a large extent, follows the five dimensions in the construction of a country-specific Renewable Energy Country Attractiveness Index (RECAI) [15], but has been revised according to the existing literature related to RE development in China.

Three main contributions can be summarized as follows: the first one is to provide a multidimensional quantitative index for accessing RE development at China's regional level. The decomposed subdimensional measures provide additional information justifying provincial advantages and disadvantages, which lead to policy recommendations. The second main contribution is using the DPCA approach to show a dynamic picture of how each dimension evolves in all provinces, which allows us to assess the trends in development. This methodology endogenizes weight determination and gives those dimensions that have larger changes higher weights. The methodology can be applied to similar index construction in other cases or other countries. Third, this paper provides a comprehensive review of the recent literature on the factors that affect RE development in China and can serve as a useful guide for any further studies on RE development in China.

The remainder of this paper starts with a comprehensive survey of the literature in Section 2, which provides the foundation for our factor selection and construction of indices. The analytical framework and the DPCA method are briefly discussed in Section 3. Section 4 reports empirical results. The last section concludes the paper with some policy implications.

2. Factors that affect RE development: A structured literature review

In the recent literature, a great deal of attention has been paid to the factors that affect the development and use of RE (e.g. Refs. [10,16–18]) in China. The content in these studies covers factors from economic variables to technological measures. Most of them base their evaluations on the country as a whole or from a broad perspective, only a few of them focus on the regional/provincial level [17,19]. Taking RECAI as a reference, these factors can be grouped into five dimensions, each of which has three to five most relevant factors for the purpose of constructing an index. One factor may contain more than one variable used in the literature, therefore, the index does not lose key information while maintaining the potential for generalization.

2.1. Economic foundation of RE development

The first and perhaps the most important driving factor in RE development is income level. The link between income and RE is based on the environmental Kuznets curve (EKC) theory, which predicts an inverted U-shaped relationship between income and environmental indicators. Given that RE is one of the key solutions to environmental problems, a simple extension to the basic EKC theory should generate a similar hypothetical link between income and the adoption of RE. Sadorsky [20,21], for example, examines the role of per-capita GDP on RE consumption and confirms the existence of a positive impact and long-run relationship in both developed and developing economies. Apergis and Payne [22] find a bidirectional causal relationship between RE consumption and economic growth for a panel of member countries in the Organization for Economic Cooperation and Development (OECD). Rafig et al. [23] compare India's and China's RE generation using data between 1972 and 2011 to confirm long-run causality from output to RE in China and bidirectional causality in India. Lin and Moubarak [24] show that economic growth in China is important for RE development using the autoregressive distributed lag (ARDL) model, and they also find reverse causality from RE to growth. Lin et al. [25] find a long-run cointegrating relationship between GDP and renewable electricity consumption in China. Chen [18] estimates a balanced panel data model using 30 provinces in China and confirms a significant, positive impact of economic development on RE consumption. Zhao and Luo [10] explicitly test the EKC hypothesis using data from China and confirm a quadratic relationship between income and RE consumption.

Another important economic factor is financial development. RE projects have greater uncertainty than traditional energy projects and are therefore costly for investors, which can lead to underinvestment. Financing obstacles are often more obvious in emerging economies with a low level of financial development [26]. Using data from 24 transition economies, Tamazian and Rao [27] find that financial market development is important for environmental performance. Kim and Park [28] confirm the positive role of financial market development in developing RE based on panel data from 30 countries. They use principal component analysis (PCA) to extract information on the development of equity and credit markets. Ali et al. [29] use a sample of 19 Asia Cooperation Dialogue member countries to study the dynamic linkages among financial development, tourism, sanitation, RE, trade, and total reserves. They also use the PCA approach to construct a financial development index based on three factors: broad money, domestic credit provided by the financial sector, and domestic credit to the private sector (all given as a percentage of GDP). The Green Finance Task Force report [30] highlights the need for a green finance system in China to support green and sustainable growth there, which gives stronger support to RE development from a financing perspective. By surveying a wide range of stakeholders, Shi at al [31]. see four financial instruments as among the top five most important instruments in promoting off-grid RE development.

Trade openness and foreign direct investment (FDI) are also considered important factors affecting RE development. They are in the general category of internationalization. Omri and Nguyen [32] study 64 countries and show that trade openness is one of the major drivers of RE consumption. Sebri and Ben-Salha [33] also consider trade openness when investigating the causal relationship between growth and RE consumption. A significant positive role has been found in Brazil, Russia, India, China, and South Africa (the BRICS countries). Chen [18] finds that exports have a positive role in RE development in China, whereas imports have the opposite effect. The main argument for including openness or FDI is that they benefit/facilitate technology transfer. FDI can also bring financing resources to the target country. Its role is, however, controversial. The well-known pollution haven hypothesis [34] suggests that FDI can cause environment deterioration in the target country. To avoid high cost and stringent environmental controls in developed country, firms may relocate their production to a less developed country with laxer regulations. Xing and Kolstad [35] find that FDI increases emissions in the target countries. Lee [36] fails to find a significant role for FDI in clean energy use in 19 of the G20 member countries between 1971 and 2009. By contrast, Luo et al. [25] find a positive role for FDI and openness in RE consumption in China. Doytch and Narayan [37] support an augmenting effect of FDI on RE consumption in their dynamic panel regression of 74 countries.

Over the past few decades, China has been one of the world's fastest developing countries, specifically in terms of urbanization [38]. The increase in urbanization level not only means a rise in urban population but also causes changes in the country's industrial structure, economic growth, the consumption level of residents, and other aspects. These changes are likely to affect China's RE consumption. Moreover, with increasing awareness of the need for environmental protection and sustainable development, urban residents have higher requirements for environmental quality. Thus, urban residents pay more attention to RE technologies, which consume less energy and create less pollution [18]. Yang and Zhang also believe that the level of urbanization is one of the main driving forces to promote RE consumption [39].

2.2. Institutions: Policies and the role of government in RE development

RE development involves clear difficulties due to high upfront costs, uncertainty, and long lags for economic benefits [40]; therefore, it has to rely heavily on government support [41]. The complexity of policy instruments available worldwide has attracted extensive studies of how much policies and policy mixes affect the development of RE. For example, Johnstone et al. [42] confirm the positive role of public policy for RE development in terms of innovation. They show, however, that the policy effects are sensitive to the types of RE sources and policy instruments. Abdmouleh et al. [43] review the available policies for RE encouragement and organize them into subcategories such as financial, fiscal, legislative, political, technological, and environmental policies. Polzin et al. [44] review the literature on many policy incentives and study the impact on RE investment across the OECD countries. Aguirre and Ibikunle [45] include a set of policy variables in their regression analysis to study the impact on RE development in 38 countries and suggest that policy design failures can impede RE investment. Darmani et al. [46] look at the institutional incentives that drive RE innovation, dividing institutional factors into hard institutions and soft institutions. Zhang et al. [47] evaluate uncertain investment decisions in low-carbon transition toward renewable energy, and they provide a clear suggestion for both the government and investor how to scientifically address uncertainty and make optimal investment decision to accelerate the low-carbon transition.

Since the REL came into effect in 2005, China has introduced a comprehensive set of policy instruments to promote RE development. Shen and Luo [48] review RE subsidy policies and their impact between 2005 and 2013. They find a combination of positive and negative effects, subject to different RE forms and policies. Lo [49] provides another review of China's RE and energy efficiency policies in six sectors. Chang and Wang [17] take the perspective of the legal system in China and suggest that the absence of a legal framework and protection has resulted in insufficient institutional support from the government and caused slow development in China's marine energy industry. They underscore the importance of financial regulation and an administrative management system. Liao and Shi [50] are the first to demonstrate that public appeals in China have a positive effect on green investment. Wang

Table 1
Variables employed to measure each dimension.

Dimension	Indicator	References	Sources
Economic foundation	GDP per capita (log)	[10,18,20–25]	*China Statistical Yearbook*
	Financial development (credit/GDP)	[26–31]	*Statistical Yearbook of China's Provinces*
	Openness (trade/GDP)	[7,18,32,33]	National Bureau of Statistics of China (NBS)
	FDI (percentage of GDP)	[7,34–37]	*Statistical Yearbook of China's Provinces*
	Urbanization	[18,38,39]	NBS
Institutions: policies and the role of government	Expenditure on environmental protection (percentage of GDP)	[41–46]	NBS
	Legal environment	[17,43,48–50]	*Marketization Index of China's Provinces* [71]*
	Government and market	[17,43]	
Technological development potential	R&D expenditure (percentage of GDP)	[51,53,55,56]	NBS
	Number of S&T employees (percentage of employment)	[10,50,53]	NBS
	High-tech market trade volume per capita (log)	[46,51,53,57]	NBS
Energy security and environmental protection	Energy deficit (electricity consumption/electricity supply)	[10,58,60]	*Statistical Yearbook of China's Provinces*
	SO2 intensity	[10,19,24,59–64]	*China Statistical Yearbook*
	Energy intensity	[60]	*China Statistical Yearbook; China Energy Yearbook*
RE sector development status	Installed capacity	[16,65]	*China Power Yearbook*
	RE share	[16,65,66]	*China Power Yearbook*
	Non-fossil fuel share	[18,45,68–70]	INEMS[72]

Note:* The marketization index in China's provinces includes information on the legal environment, government, and market.

et al. [51] used a non-radial DEA method to measure new energy enterprises' innovation efficiency in China. They proposed that enterprises should implement targeted improvement strategies based on efficiency characteristics.

2.3. Technological development potential of RE

As a newly developed sector, the RE industry has heavy demand for technology, and technology is key to its progress. For example, Fischer et al. [52] set up an analytical framework to show that technological subsidies can contribute to RE development and act as a supplement to RE standards. Although a follower at the outset, China caught up to other nations in its recent technological progress [53]. For example, in the solar PV industry, Japanese and German companies were the leaders before Chinese firms surpassed them in 2010. By 2012, seven out of the world's top 10 PV producers are based in China [54].

R&D investment in RE, especially long-term government support is crucial [55]. Zhao and Zhang [56] include R&D expenditure in their empirical model based on a panel of solar PV firms in China. Their analysis shows that the way to obtain future development in the Chinese PV industry is to rely on technological progress and market competition. Darmani et al. [46] include technology infrastructure in their analysis and argue that knowledge infrastructure is an important part of the innovation system. Taalbi [57] investigates the driving factors in innovation through a review of existing theories and finds that a market structure that ensures returns for innovation has positive effects. The study also finds that it is important to have a stock of knowledge. Zhao and Luo [10] find that employment can promote development of RE.

2.4. Energy security and environment protection

As in the construction of RECAI [15], energy security and environmental factors in a region are important in evaluating its RE development. First, RE development is relevant to the issue of energy security [58]. It is then followed by increasing concerns over environmental degradation in China. Burning fossil fuels has exposed people across China to air pollution and caused significant socioeconomic losses [59]. Zhao and Luo [10] suggest that environmental concerns and energy security are in part the driving forces for China to support RE development. Zhang et al. [60] suggest that RE development can serve as a long-term solution for the energy shortages, low efficiency, high emissions, and environmental impacts of traditional fossil fuel energy. In other words, a region with a higher level of energy security and environmental concerns tends to have more motivation for developing RE.

Most of the existing cross-country studies use CO_2 emissions as a proxy for environmental incentives for RE development (e.g. Refs. [19,61–63]). Lin and Moubarak [24] use CO_2 emissions in the estimation of a growth-RE consumption nexus in China. CO_2 emissions, however, are not available at the provincial level, and they do not have clear proxies. Alternatively, sulfur dioxide (SO_2) emissions can be used for the same purpose [64], which is also more relevant to provincial environmental concerns in China.

2.5. Status of RE sector development

RE is distributed unevenly in China, with clear spatial disparities of all types of RE sources [16]. For example, wind energy is mainly in the 3 N regions, whereas western Tibet, northwestern China, northern China, and parts of northeastern and southwestern China have high annual solar radiation. Although new technology allows new sources to be exploited in other regions, the existing *installed capacity* can be a good indicator of natural endowments and therefore potential future development. On the demand side, the share of renewables in total power generation (*RE Share*) is a popular target in national policy. This is consistent with the statement 'Several Opinions on Further Deepening China's Power System Reform' issued by the State Council in 2015, which emphasizes that increasing the proportion of the RE power supply is a principle of reform [65]. Liu et al. [66] explicitly show the unevenly distributed RE sources across China and further discuss the potential RE sources in terms of the RE share.

Increasing the non-fossil fuel share is the key to addressing climate change and low CO_2 economic development in China [18]. The energy situation in China is characterized by a heavy dependence on coal, whose share of the country's primary energy supply in 2014 was 65.6%, followed by oil (17.4%), natural gas (5.7%), and hydropower/nuclear (8.7%) [67]. The 'lobby effect' in RE adoption, documented in Aguirre and Ibikunle [45], implies the influence of traditional energy sources in undermining the adoption of RE. It is assumed that the higher the consumption of fossil fuel is, the more difficult it is to adopt RE. Other studies also find a significant impact of the 'lobby effect' on RE adoption [68–70].

2.6. Analytical framework for RE development: the five dimensions

Following the structured literature survey above, and also referring to the five dimensions established by RECAI, we now introduce a multidimensional framework, which also includes five dimensions: economic foundation, institutions, technological development potential,

Table 2
Regions and provinces in China.

Regions	Provinces and province-level municipalities
Eastern region	Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan
Central region	Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan
Western region	Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia

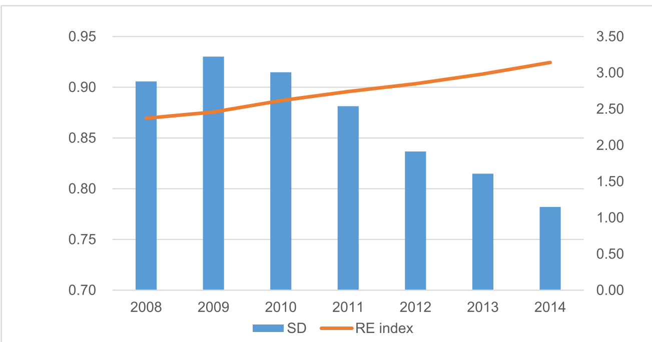

Fig. 2. Average RE development in China, 2008–2014. Note: The left-hand axis is for the RE index, and the right-hand axis is for the standard deviation (SD).

energy security and environmental protection, and RE sector development status. The choice of variables in each dimension is explained in Table 1 with support from the existing literature. In addition, a brief justification of the dimensional setups is given as follows:

Although RE development is supported by the demand for cleaner energy and a cleaner environment, its actual progress is constrained by the level of regional economic development. Economic foundation is measured by the levels of GDP per capita, financial development, openness, FDI, and urbanization. Higher GDP per capita indicates that a region is more likely to realize interest in RE development. Greater financial development is positively related to RE development, as it is more likely to indicate access to finance. Trade openness and FDI are considered important factors that affect RE consumption. Urbanization is one of the main driving forces behind the promotion of RE consumption as well.

The dimension of institutions, policies, and the role of the government measure policy support from regional governments. This dimension is represented by environmental protection expenditures; legal environment, which measures how seriously a policy is enforced; and the government and market, which measure the degree of government intervention in the market.

We also estimate the potential for future growth in RE in a region by the share of R&D expenditure in total GDP and the number of employees in science and technology, which are positively connected to the future generation of RE technology. The trading volume in the high-tech market measures the market condition for innovation, which indicates the likelihood that R&D has been commercialized and thus is positively related to future technological development potential.

The dimension of energy security and environmental protection measures the demand side drivers of RE development. A large local deficit in electricity supply will motivate a region to develop RE, which is not dependent on traditional energy reserves. SO_2 intensity will also encourage a region to seek RE energy, which will not cause air pollution—a top concern of local government. Development of RE energy is an effective measure for reducing energy intensity, which is specified as a key performance indicator for regional governments by the central government. For example, coal-fired power plants transfer no more than 40% of primary energy supply to electricity (final energy demand), while RE has higher transformation efficiency. Furthermore, decentralized RE can also avoid distributional losses.

Finally, we measure the development of RE industry with three variables: installed capacity, the share of RE in total power generation, and the share of non-fossil fuel consumption in total energy consumption. The first and third variables measure the progress of RE development from the perspective of supply and consumption, respectively, while the second variable measures the actual contribution of RE. Factors that limit the performance of RE generation capacity, such as weather and curtailment, have contributed to the difference between capacity and actual generation.

3. Empirical methodology

Our methodology is the DPCA approach, which is used to construct an index to measure the level of RE development in each province over time. Evaluating RE development has attracted enormous attention in the existing literature. Many empirical strategies have been applied to assess RE development, for example, the metafrontier approach [73], the conceptual modelling approach [74], the non-radial DEA approach [51], and the real option approach [47]. These methods are quite useful

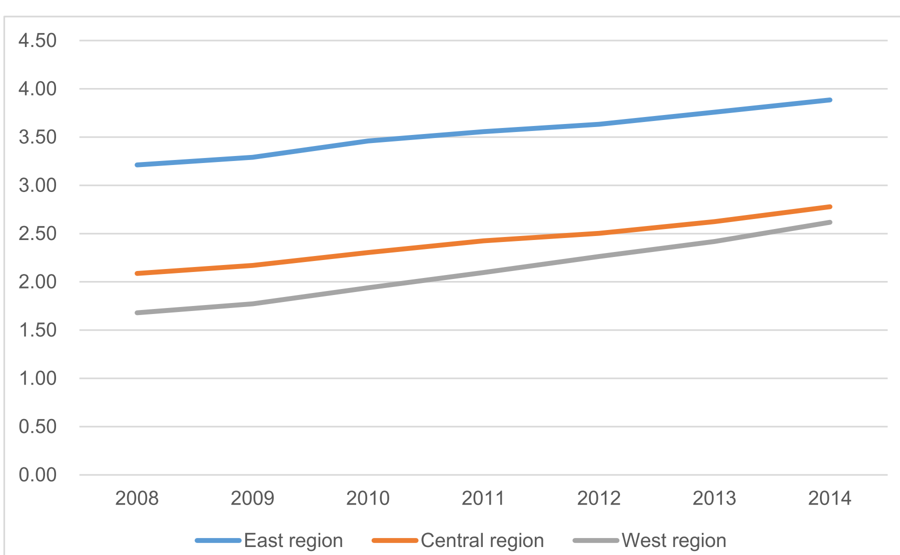

Fig. 3. Average RE development in the three regions in China.

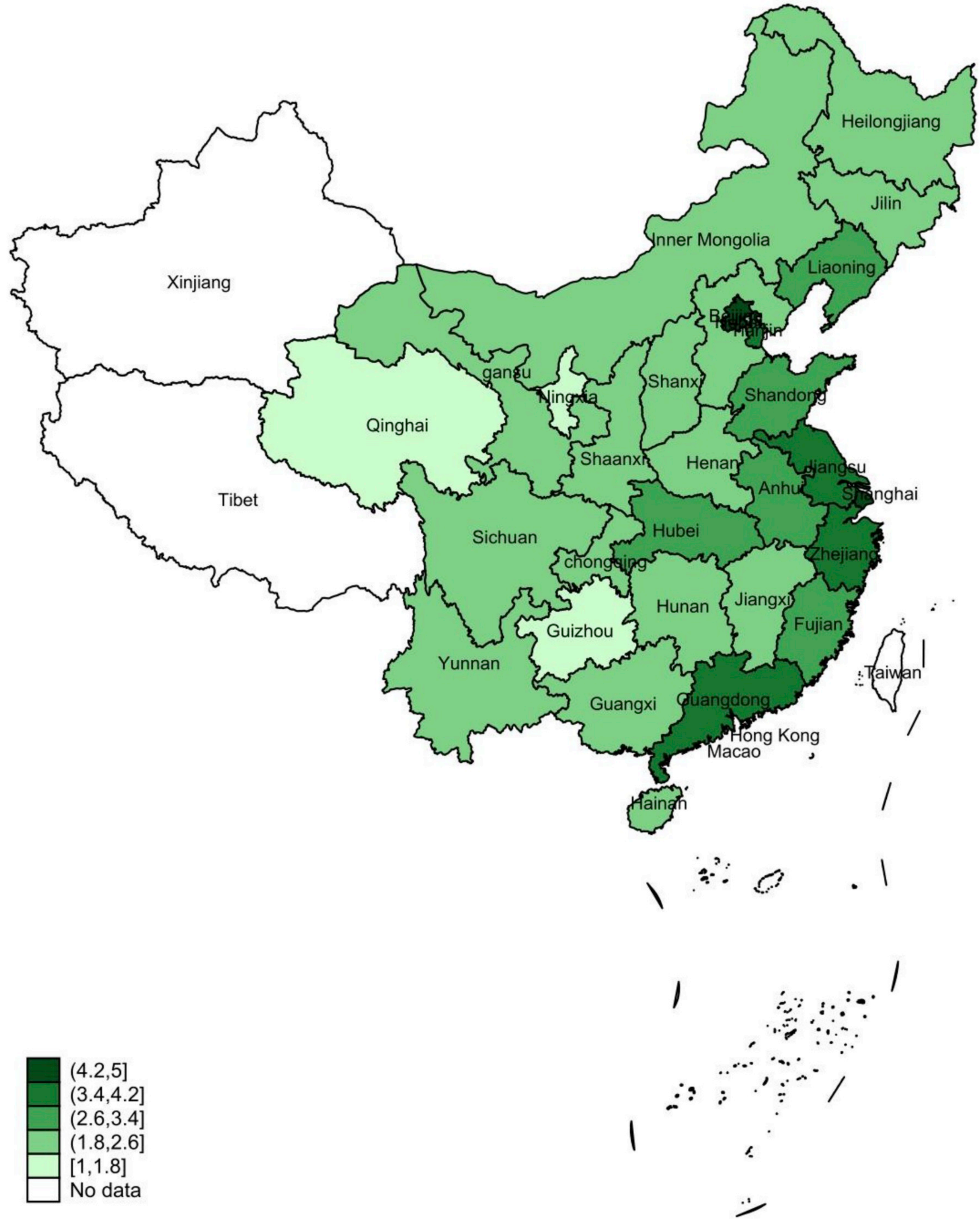

Fig. 4. Renewable energy development indices in China.

to measure efficiency and understand the decision making process. In this paper, the main objective is to provide a multidimensional evaluation framework, therefore the PCA approach [75–80] is the most appropriate one.

3.1. Dynamic principal component analysis

DPCA was applied twice to calculate the overall score for development in the RE industry. First, we used DPCA to generate a single index for each of the five dimensions of RE development. Second, we used DPCA again to combine these five indices into an overall index of RE development. Last, the RE development index scores for each province were standardized between one and five.

PCA is a widely used statistical method for dimension reduction, and the main idea is introduced by Pearson [76]. In terms of RE development, Lee and Zhong [77] use the PCA approach to establish a Renewable Energy Responsible Investment Index (RERII) for 50 countries. Their 17 indicators are divided into four groups: economic, environmental, social, and country governance. Wang et al. [78] deliver a regional evaluation of RE vulnerability to climate change in China. They combine the PCA method and a Grey cluster analysis (GCA) to investigate three areas of RE vulnerability: exposure, sensitivity, and adaptive

Table 3
Ranking of provinces on RE development, 2008 and 2014.

R_{2008}	Province	Index	R_{2014}	Province	Index	Change in Rank
1	Beijing	4.61	1	Shanghai	5	1
2	Shanghai	4.46	2	Beijing	4.74	−1
3	Guangdong	3.73	3	Guangdong	4.55	0
4	Zhejiang	3.63	4	Zhejiang	4.4	0
5	Jiangsu	3.47	5	Jiangsu	4.2	0
6	Tianjin	3.41	6	Tianjin	4.08	0
7	Fujian	2.73	7	Fujian	3.5	0
8	Shandong	2.59	8	Liaoning	3.42	1
9	Liaoning	2.58	9	Shandong	3.25	−1
10	Jilin	2.3	10	Anhui	3.18	2
11	Hubei	2.3	11	Chongqing	3.05	2
12	Anhui	2.29	12	Hubei	3.03	−1
13	Chongqing	2.2	13	Gansu	2.97	12
14	Hainan	2.18	14	Heilongjiang	2.87	1
15	Heilongjiang	2.16	15	Inner Mongolia	2.85	9
16	Sichuan	2.11	16	Shaanxi	2.83	1
17	Hunan	2.08	17	Hebei	2.81	4
18	Shaanxi	2.04	18	Hainan	2.79	−4
19	Jiangxi	2.04	19	Jilin	2.78	−9
20	Henan	2.01	20	Sichuan	2.73	−4
21	Hebei	1.94	21	Henan	2.68	−1
22	Guangxi	1.86	22	Jiangxi	2.67	−3
23	Yunnan	1.82	23	Hunan	2.64	−5
24	Inner Mongolia	1.66	24	Guangxi	2.5	−2
25	Gansu	1.58	25	Yunnan	2.46	−2
26	Shanxi	1.51	26	Shanxi	2.37	0
27	Qinghai	1.4	27	Ningxia	2.37	1
28	Ningxia	1.11	28	Qinghai	2.24	−1
29	Guizhou	1	29	Guizhou	2.18	0

capacity.

Our empirical model takes an alternative approach and uses dynamic PCA (DPCA), illustrated by Federici and Mazzitelli [79]. The dynamic approach has been applied by Zhang et al. [80] to investigate energy market integration in East Asia and is a useful tool for obtaining a picture of development in both cross-section and time dimensions.

According to Federici and Mazzitelli [79], this method combines a cross-section analysis through PCA and time-series dimension of data. The data arrays comprising three dimensions (units, variable, and time):

$$X(I,J,T)=\{X_{ijt}\}\ i=1,\cdots,I;j=1,\cdots,J;t=1,\cdots,T$$

where i is the unit, j is the variable, and t is time.

Combining the cross-section analysis through PCA and the time-series dimension of data in a linear regression model decomposes the variance and covariance matrix S related to X (I, T, J), in which the units are identified by the pair "unit-time," in the following variance and covariance matrices:

$$S={}^{*}S_I+{}^{*}S_T+S_{IT} \tag{1}$$

${}^{*}S_I$ is a matrix of the static structure of the units, reflecting the variability of the relational structure of the units, independently from the time dimension. ${}^{*}S_T$ is a matrix of the average dynamic of the system, which represents the variability in the average of the units, independently from the dynamic of single units. S_{IT} is a matrix of the differential dynamic of single units, showing the variability due to the difference between the dynamic of the overall average of the units (the average dynamic) and the dynamic of single unit.

The model is based on the decomposition of total variability into two components.

$$S=({}^{*}S_I+S_{IT})+{}^{*}S_T=S_T+{}^{*}S_T \tag{2}$$

S_T is the average dispersion matrix within time, ${}^{*}S_T$ is the average dispersion within variability modelled through a linear regression model of the following form:

$$\overline{x}_{\cdot jt}=a_j+b_jt+e_{jt}\ j=1,\cdots,J;t=1,\cdots,T \tag{3}$$

where the residuals satisfy the condition:

$$\mathrm{cov}(e_{jt},e_{j't'})=\begin{cases} w_j & j=j';t=t' \\ 0 & j\neq j';t\neq t' \end{cases} \tag{4}$$

This condition has to be taken into consideration because the relationship between the j variables is explained only by PCA relative to the S_T matrix. In other words, it implies that the average dynamic of the system is distinct from the average dynamic of single variables.

The principal components are weighted with the corresponding proportion of variance in the original set of variables explained by the particular principal component, and the overall index is computed using the following equation:

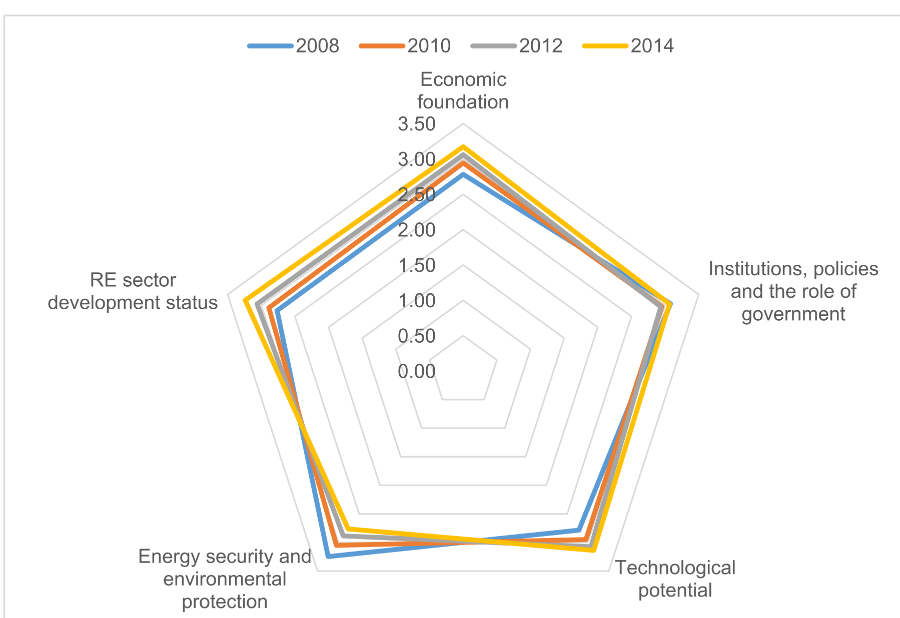

Fig. 5. Relative strength in five different fields of average RE development, 2008–2014.

Table 4
Rank for of the components of RE development.

Province	Economic	Institutions	Technology	Energy and environment[a]	RE sector development	Overall scores
Shanghai	1	3	2	2	21	1
Beijing	2	6	1	1	22	2
Guangdong	4	5	5	3	1	3
Zhejiang	5	2	6	5	2	4
Jiangsu	6	1	4	6	6	5
Tianjin	3	4	3	4	28	6
Fujian	8	7	16	8	10	7
Liaoning	7	11	9	12	5	8
Shandong	11	8	11	10	13	9
Anhui	19	9	7	15	27	10
Hubei	16	10	10	20	17	11
Chongqing	9	16	12	13	29	12
Jilin	15	20	18	16	7	13
Heilongjiang	13	18	14	18	8	14
Hainan	10	23	28	7	16	15
Shaanxi	21	21	8	22	26	16
Sichuan	22	13	17	21	25	17
Inner Mongolia	12	25	22	25	3	18
Jiangxi	17	14	23	9	20	19
Hebei	23	19	27	19	9	20
Henan	26	12	24	14	24	21
Hunan	24	17	19	11	19	22
Guangxi	27	15	29	17	23	23
Gansu	28	27	15	24	4	24
Yunnan	25	22	25	23	14	25
Shanxi	20	24	20	27	15	26
Ningxia	14	28	21	29	11	27
Qinghai	18	29	13	26	12	28
Guizhou	29	26	26	28	18	29

[a] Considering that the load of energy security and environmental protection is negative, so this dimension shows items in the reverse order of the others, so that every dimension has a positive effect on RE development.

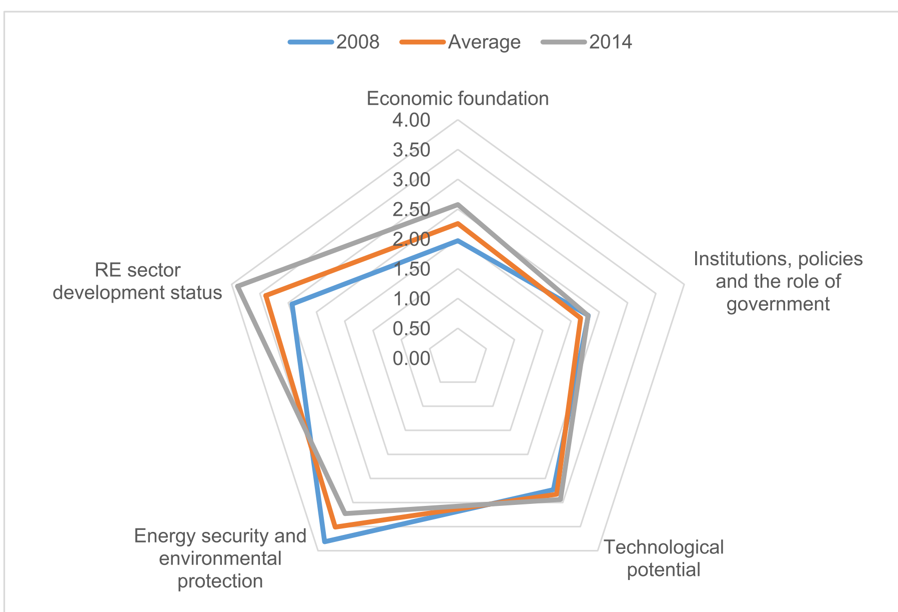

Fig. 6. Relative strength in five dimensions of average RE development in Gansu.

$$V = \sum_{i=1}^{m} (\omega_i F_i) \Big/ \sum_{i=1}^{m} (\omega_i) \tag{5}$$

where V is the value of the overall index, and ω_i is the proportion of variance explained by the i th principal component. The bigger the value of *V,* the better the RE development situation is, and vice versa.

3.2. Data

We collected provincial data in China from 2008 to 2014, covering seven years and 29 provinces (excluding Xinjiang and Tibet, for which certain data are not available). Detailed descriptions of dimensions and their subsequent indicators are in Table 1.

For the convenience of presentation, we group the 29 provinces regionally. In China, its provinces are usually divided into three major regional groups: eastern, central, and western [81,82]. In the energy

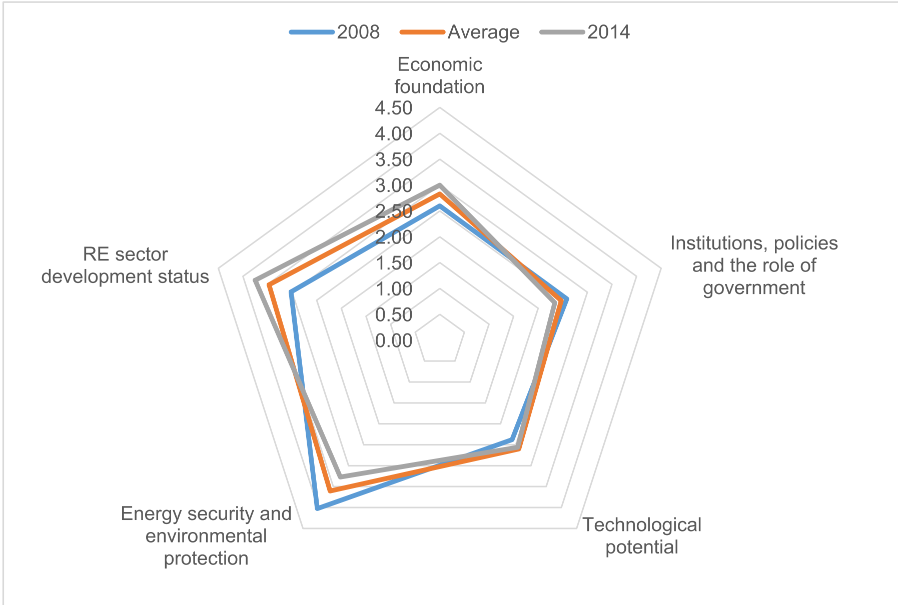

Fig. 7. Relative strength in five dimensions of average RE development in Inner Mongolia.

performance literature, it often found that the eastern region is the most developed while the western region is the least developed [83]. Detailed information on the regions and provinces is shown in Table 2.

As shown in Table 2, the eastern region comprises eight coastal provinces (Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan) and three provincial-level municipalities (Beijing, Tianjin, and Shanghai). This region has experienced the most rapid economic growth in China over the past 40 years. Most light industry and quite a bit of heavy industry, as well as most service industries in China, are located in the eastern region. The eastern region has also attracted the most foreign investment, technology, and managerial expertise. Beijing and Shanghai are considered the most economically and socially developed areas in China.

The central region consists of eight inland provinces: Heilongjiang, Jilin, Henan, Shanxi, Anhui, Hubei, Hunan, and Jiangxi. This region has a large population and is the main location of agriculture and related industries. Foreign investment and technology level in this region is relatively lower than those in the eastern region. Shanxi is one of the largest provinces in the country in terms of its energy industry, which produces and exports millions of metric tons of coal to the eastern region each year. Because of the high density of heavy industry in some of the provinces in this region, energy consumption and related pollutant emissions are quite high.

The western region covers more than half the territory of China and includes nine provinces—Inner Mongolia, Guangxi, Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Yunnan, and Sichuan—and the municipality of Chongqing. This region has low population density compared to the other two regions and is the least developed region in China. But it has high traditional resource reserves, such as coal, oil, natural gas, and minerals, along with abundant renewable energy resources, such as wind and solar power. Inner Mongolia and Gansu are two of the main locations for wind power development in China.[2]

[2] It is worth clarifying again here that our study on RE development is not limited to wind and solar power. These two energy forms are, however, the REs the most policy relevance, and thus their installed capacity and share are used by China Power Yearbook. We appreciate an anonymous reviewer for his valuable comments.

4. Empirical results

Using the DPCA approach, we constructed an index to measure the level of RE development in each province in China between 2008 and 2014. Eigenvectors of DPCA analysis are presented in the Appendix (Tables A1 and A2). The empirical results on both the aggregate and province-specific measures are reported and discussed below.

4.1. RE development in China

Over the whole sample period, the RE industry in China has made significant progress. The average RE index (simple average of province-level RE development indices measured by DPCA) increased from 2.37 in 2008 to 3.14 in 2014, while the standard deviation for the same periods declined from 0.91 to 0.78 (Fig. 2). This decreasing standard deviation suggests that the extent of disparity has narrowed, and regional RE performance is converging.

All three regions experienced increases in RE development, but with distinct differences among them (Fig. 3). Fig. 3 shows that (1) the eastern region exhibited the highest average improvement in RE development in all years, at 3.53, ranging from 3.21 to 3.89; (2) in the central region, the average RE score was 2.41, ranging from 2.09 to 2.78, which paralleled that of the eastern region; (3) in the western region, RE development lagged behind the other two regions, but improved more quickly, ranging from 1.68 to 2.62. The performance gap between the eastern and central regions did not change, but the gap between the western region and the other two shrank.

The RE development results based on DPCA in China's 29 provinces are illustrated in Fig. 4, which shows the average RE development values between 2008 and 2014. Beijing and Shanghai have the highest level of RE development. Guangdong, Zhejiang, Jiangsu, and Tianjin ranked in the second tier. Provinces in the western region such as Ningxia, Qinghai, and Guizhou, have the lowest RE development.

Improvement over time varies across provinces. Shanghai, Beijing, Guangdong, Zhejiang, Jiangsu, Tianjin, Fujian, Shandong, and Liaoning consistently remained in the top nine throughout the sample period. Their index values have all increased between 2008 and 2014 (shown in Table 3), which indicates a general improvements in their RE developments. The difference between the maximum and minimum values in 2008 and those in 2014 declined from 3.61 to 2.82, which again reveals convergence across provinces.

In Table 3, R-2008 and R-2014 represent the rank in RE development in 2008 and 2014 respectively. The largest jump in ranking was attained by Gansu and Inner Mongolia, whereas Jilin and Hunan recorded the biggest decline in ranking. For example, Gansu's index values are $V_{2008} = 1.58$ and $V_{2014} = 2.97$. Its rank for RE development was only the 25th in 2008, but gains 12 positions to the 13th nine years later ($R_{2008} = 25$ and $R_{2014} = 13$).

4.2. Dimensional assessments of renewable energy development

After presenting changes in the overall RE development level, we further investigate the contribution of each dimension to RE development. A comparison of RE indexes from 2008 to 2014 shows that they have consistently increased over time in three dimensions: economic foundation, RE sector development status, and technological development potential (Fig. 5). Meanwhile, the dimension of energy security and environmental protection decreased during all years. At the same time, the institutional dimension made no significant progress during the sample period. It first experienced decline, and then increased to regain the original level, which shows that the institutional dimension is more challenging than the other four dimensions.

In Table 4, we can identify provinces whose particular combinations of factors warrant greater attention or provide an interesting combination of factors for further evaluation. For example, Zhejiang, Guangdong, and Jiangsu rank 1, 2, and 6 respectively, and they achieve balanced development across the dimensions, whereas Shanghai, Beijing, and Tianjin are restricted by their RE sector development status, mainly because of limits in their RE resources.

The resource-rich provinces often have commendable RE sector development, but their development in the other four dimensions is limited. Inner Mongolia and Gansu, which have abundant wind power, do well at RE sector development status but are limited in the other four dimensions. Liaoning, Jilin, and Heilongjiang have similar natural endowments, but the drivers of their level of RE development differ greatly. Liaoning is driven mainly by RE sector development, economic foundation, and technology potential. Jilin and Heilongjiang are driven mainly by RE sector development status but restricted in the other four dimensions, which explains why these two provinces fall behind.

4.3. Dimensional assessments of provinces experiencing the largest jump

Gansu and Inner Mongolia made the largest advances over time and have similar conditions. They showed a significant increase in RE sector development status and economic foundation, whereas a significant decline in energy security and environmental protection between 2008 and 2014 is found. Both of them experienced a marginal rise in technological development potential. The institutional dimension did not change much over these years, as Gansu experienced first a decline and then an increase to the original level, and Inner Mongolia showed a slight drop (Figs. 6 and 7).

5. Conclusion and policy implications

This paper uses DPCA to measure RE development and change in 29 Chinese provinces from 2008 to 2014 over five dimensions. The method is applied twice, first to construct an index for each dimension and then to aggregate the five dimensional indices to generate a single RE development index.

The results show that RE development in China has improved over time, with the disparity in RE development across provinces growing smaller. The average RE index increased consistently by 0.77 over the whole sample period. However, the level of RE development in China still has large regional imbalances. Generally speaking, it is strongest in the eastern region, and weakest in the western region with the central region generally in between. The growth rate in the western region is however, higher than in the central and eastern regions.

Among all the provinces and province-level municipalities, Beijing and Shanghai have the highest level of RE development, followed by Guangdong, Zhejiang, Jiangsu, and Tianjin, and then Fujian, Liaoning, and Shandong. Anhui and Hubei have an average level of RE development. All of these provinces, except the last two, are in the eastern region. The resource-rich areas in the northeastern, central, and western regions often have outstanding RE development status but relatively poor in the other four dimensions.

The largest improvement in ranking was achieved by Gansu and Inner Mongolia, mainly due to their progress in the dimensions of economic foundation, energy security, and environmental protection, and RE sector development status. But they are all limited in their degrees of institutional development.

Our analysis demonstrates that regional RE systems have no single driver or underlying mechanism. Rather, provinces experienced RE development due to a unique combination of various factors, as demonstrated in the five dimensions. Across the board, the institutional dimension is the most challenging part of RE development.

This study has three useful policy implications. First, every province should adopt different and specific strategies in RE development. For example, Beijing and Shanghai should make an effort to address their RE sector development dimensions. Inner Mongolia and Gansu have the most wind power, so they should enhance their capacity in terms of the other dimensions, and so should Jilin and Heilongjiang.

Second, other than RE technology and adoption, the institutional dimension, mainly policies and governance, is an important area in which individual provinces in China should increase their efforts. As shown in the previous section, institutions first experience decline and then increase to their original levels. This indicates the existence of a possible institutional barrier for RE development. Because the government plays a large role in industrial development and has the most responsibility for the legal and market environment, it is the lead actor in facilitating progress in developing RE. This is particularly important in resource-rich provinces. For them, improvements in the four areas other than RE development could significantly improve their overall RE development and thus help the nation as a whole to accelerate RE penetration.

Finally, provinces that lag behind can learn from those advanced peers, especially with similiar conditions. As shown in the previous section, Zhejiang, Guangdong, and Jiangsu have achieved balanced development in all dimensions, offering a good example for other provinces to follow. Jilin and Heilongjiang could learn from Liaoning province because they share similar conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Results of DPCA analysis based on the five dimensions aggregated

Component	Eigenvalue	Proportion	Cumulative
1	20.2638	0.6098	0.6098
2	5.9533	0.1791	0.7889
3	4.7969	0.1443	0.9332
4	1.4769	0.0444	0.9777
5	0.7409	0.0223	1

Table A2
Eigenvectors of DPCA analysis based on the five dimensions aggregated

Variable	e1	e2	e3	e4	e5
Economic	0.0590	0.9800	−0.1565	−0.0363	−0.1020
Institutions	−0.4676	0.1361	0.4754	0.7311	0.0481
Technology	0.5012	−0.0802	−0.5293	0.6737	0.0914
Energy & environment	0.5066	0.1183	0.4967	−0.0665	0.6915
RE status	0.5196	−0.0267	0.4718	0.0770	−0.7076

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