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A bibliometric analysis based review on wind power price

Cuixia Gao [a], Mei Sun [a,*], Yong Geng [b,*], Rui Wu [c,d], Wei Chen [b]

[a] Center for Energy Development and Environmental Protection, Jiangsu University, Zhenjiang, Jiangsu 212013, China
[b] School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[c] Key Lab of Pollution Ecology and Environmental Engineering, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[d] University of Chinese Academy of Sciences, Beijing 100049, China

HIGHLIGHTS

- In order to promote the application of wind power, appropriate wind power price should be regulated.
- A bibliometric analysis approach is employed to review the progress of wind power price.
- Research hotpots on wind power price were identified.
- Future research directions on wind power price were proposed.

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ABSTRACT

With the increasing negative effects of fossil fuel combustion, many countries have paid more attention on supporting environmentally friendly energy generation, particularly renewable and sustainable energy sources (RES). However, renewables still cannot economically compete with fossil-fuels and are facing new challenges. Appropriate electricity pricing mechanism plays a vital role on mitigating the stress of limited fossil fuels and can promote renewable energy consumption. As one major type of renewable energy, wind power has been globally promoted. In order to promote the application of wind power, appropriate wind power prices (WPP) should be established by considering the local conditions. This paper targets such a field and conducts a bibliometric and network analysis based on the data from Scopus. The results show that the numbers of total related publications are gradually increasing, with the US as the leading country. European countries also have outstanding achievements. Moreover, both the most cited articles and keywords distribution offer future research directions. In general, this study provides valuable insights to both wind power researchers and practitioners.

Contents

* Corresponding authors at: No. 301 Xuefu Road, Zhenjiang, Jiangsu 212013, China (M. Sun). No. 800 Dongchuan Road, Minhang, Shanghai 200240, China (Y. Geng).
E-mail addresses: sunm@ujs.edu.cn (M. Sun), ygeng@sjtu.edu.cn (Y. Geng).

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Nomenclature

WPP	wind power price	CIC	cumulative installed capacity
RES	renewable energy sources	TC	total citations of articles
R&D	research and development	ACPP	average citations per year per article
MOE	merit order effect	PES	IEEE Power and Energy Society General Meeting
NO	number of articles	NAIC	new added installed capacity

1. Introduction

With more emerging global issues, such as climate change, energy security and environment deterioration, the exploitation and utilization of renewable and sustainable energy sources (RES) have been accepted as one key element of the world's future energy strategies [1–3]. However, the electricity generation from RES cannot economically compete with fossil-fuels generated electricity and are facing new challenges, such as uncertainty, specific locations, and variability [4–10]. Nevertheless, due to lower environmental impacts and CO_2 emissions, RES has been promoted as one key measure to respond climate change. Among the available RES, wind energy is currently regarded as one of the most significant, fastest growing, and commercially attractive sources to generate electricity because of the mature and cost-effective wind energy technologies [11–15]. By the end of December 2014, the global wind power capacity expanded to 369,553 MW. The newly added installed capacity (NAIC) of global wind generation has had an average annual growth rate of 25% since 1996, as shown in Fig. 1. But due to several political, social, and economic reasons, to further increase wind power production will require better integration of wind power into power grids [16–21]. However, wind curtailment frequently occurs. In particular, the higher wind turbine costs, related infrastructure costs and wind power prices have impeded the wide application of wind energy [22]. Under such a circumstance, how to establish a reasonable wind power price (WPP) mechanism has become urgent in order to reduce wind curtailment and promote more reasonable allocation of renewable energy.

Currently, WPP mechanism can be mainly divided into three categories. The first one is the fixed price, implemented in Germany, Denmark, Portugal and Spain. The second one is the tender price implemented in the United Kingdom, Canada, Ireland, and France. This means that the lowest price will win through the project bidding according to the government's plan on wind power installation capacity. The third one is the renewable energy quota system, mainly implemented in Japan. It is an indirect measure to support wind power which requires remaining a certain percentage of RES in the total electricity mix [23,24]. Wind power price contains bidding in the day-ahead market, merit order effect (MOE) of wind power penetration, and renewable energy support schemes such as feed-in tariffs for end users. To strengthen academic study on wind power price is an effective way to accelerate wind energy development so that the national energy structure can be adjusted. It involves many factors, including specific costs (power output as well as the investment, financing, operating and maintenance costs), market prices, subsidies, etc., [25–30]. Meanwhile, it refers to power producers, consumers and service corporations. For example, Finn and Fitzpatrick [31] analyzed the potential for the implementation of price-based demand response by an Ireland industrial consumer to increase their proportional use of wind electricity and found that price optimization resulted in a fortuitous increase in wind energy consumption. Vilim and Botterud [16] analyzed wind power trade and prices in electricity markets by investigating two electricity imbalance pricing schemes, showing that both bidding strategies have advantages over the assumed 'default' bidding strategy. Bhaskar and Singh [32] proposed a stochastic model for optimal bidding of wind

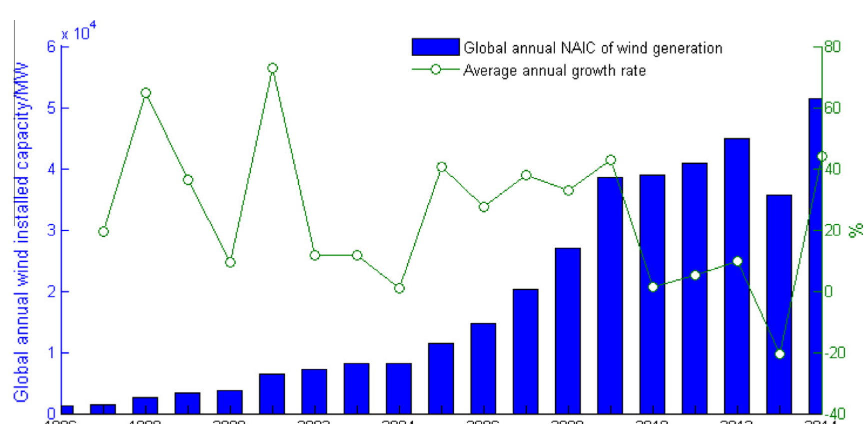

Fig. 1. Global annual NAIC of wind generation (MW) during 1997–2014.

power in a day-ahead electricity market in which the uncertainties due to wind power generation and market prices were characterized. He et al. [33] designed four kinds of feed-in tariff mechanisms and established a benefit distribution model to analyze the wind power stakeholders' benefits. McKenna et al. [34] determined that the economic potential based on current levels of subsidy, i.e. feed-in tariffs of around 9 ct/kW h, varies with the employed discount rate from around 400 TW h/a with 11% to about 800 TW h/a with 5%, for the electricity generation from wind in Germany.

Academically, many papers have been published on the issue of wind power price. However, none of them presents a comprehensive overview on wind power price from both quantitative and qualitative views. Also, none provides a holistic and quantitative overview on WPP related publications by conducting bibliometric analysis and complex network analysis. Consequently, this study tries to fill this gap. Bibliometric analysis has been widely adopted to trace relationships amongst academic journal citations. It is a set of methods to quantitatively analyze scientific and technological literatures [35,36]. Under such a circumstance, this paper aims to figure out the evolution pathway of wind power price related studies by employing bibliometric analysis so that future research directions can be recognized. Main contributions of this paper include: (1) This study aims to evaluate the current research progress and trends of wind power price research and its applications. (2) Several publication characteristics such as journals, countries, research institutions and the most cited articles are presented. (3) This study lists the distribution of keywords according to research subjects, purposes, methods, and research fields. (4) The results are further discussed so that potential research directions for future studies can be identified.

The whole paper is organized as below. After this introduction section, research methods are described in Section 2, including data sources and treatment. Section 3 presents empirical results and discusses research results. Finally, section 4 draws research conclusions and provides policy implications.

2. Methods and data

2.1. Methods

Bibliometric analysis was defined by Pritchard as the application of mathematics and statistical methods to books and other media of communication [37]. Two widely used bibliometric methods are citation analysis and content analysis. Citation analysis implies a relationship between citing and cited works in a particular research area and allows one to identify core literatures, journals, countries, etc., [38]. Different from citation analysis, content analysis aims to identify current hotspots on the basis of frequency of author keywords and other distributions. In general, bibliometric analysis offers a useful tool to shift from micro (scientist and institute) level to macro (national and global) level. Furthermore, the research trends and popular issues in the study fields can be identified by employing such a method [39–43].

Network analysis can help clarify the relations among different items by underlying a network of nodes and links through which information or social relationships travel. In this paper network analysis is conducted in order to establish a network with the nodes that represent research articles, keywords, or countries. Such a network can help evaluate the importance and influence of a node by measuring the centrality of the nodes. Among various software tools, Gephi is frequently used for the visualization of networks. Bibexcel is another software tool to perform bibliometric and network analysis [44,45]. In this study, the complex network analysis is undertaken to analyze the academic collaboration among different countries and authors by using both Bibexcel and Gephi.

The problem of identifying whether the nodes play a core role is one of the main topics in the traditional analysis of complex network. One of the centrality measures is the degree of nodes [46,47]. The degree distribution of a network is used to describe the distributing characteristic of the number of connections that one node has and to study the heterogeneity of one node. If nk nodes have the same degree k, the degree distribution $p(k)$ is defined as $p(k) = nk/n$. If the degree distribution can be fit with a power law distribution $p(k) = k^{-\gamma}$, it is taken as a sign that the network has obvious heterogeneity. In addition, $-\gamma$ is the power-law index and k is the node degree. In this paper, we use degree distributions to depict the whole distribution features of author keywords. It demonstrates that the distribution of WPP author keywords is uneven and most of the numbers are concentrated in a few keywords.

2.2. Data collection and treatment

The Scopus database is used to compile the literature data set since Scopus provides comprehensive and standardized exporting data and has been widely used by academia. Two keywords (wind power price and wind electricity price) were used to search the related publications published during the period of 1997–2014. The search was conducted in July 2015, and 2359 documents were found. Of all publications retrieved from Scopus, peer-reviewed research articles account for 49.08%, followed by conference papers (38.88%), review papers (4.3%), and others (e.g. book chapters, conference reviews, notes, short surveys, business articles, articles in press, books, letters and reports). Similarly, English (92.65%) is the most frequently used language for such a search, followed by Chinese (2.97%), German (2.49%) and others. In order to provide an international perspective, only research articles, conference papers and review papers published in English are further analyzed in this paper. Finally, a total of 1994 documents were reserved for further analysis.

Several notes should be presented, which relate with data processing. First, the national property of one paper depends on its first author when the authors come from different countries. If the first author has more than one nationalities, then only the full address of its first author is considered for identifying his/her nationality. Second, some keywords may have different appearances although they have the same meanings, such as "Stochastic programming" and "Two-stage stochastic programming", "Life Cycle Analysis" and "Life cycle assessment". In order to solve such a problem, these keywords that have the same meanings are regarded as one keyword. Third, one reference cited by different articles may have different forms. In order to standardize it, references that share the same digital object identifier (DOI) are transformed into one reference.

3. Results and discussions

3.1. The performance of related publications

Fig. 2 presents the annual numbers of published articles (NO), total citations of articles (TC), average citations per year per article (ACPP) and the top 3 publication countries during the period of 1997–2014. It is clear that the NO increased slowly in the first 8 years and then experienced a quick increase in 2006. In the year of 2005, the group of seven (G7) countries, including the United Kingdom, Canada, France, Germany, Italy, Japan and the U.S., held a meeting to discuss how to encourage the development of alternative energy sources in order to respond higher crude oil prices. This event drove the U.S. to release a new energy regulation to encourage companies to use renewable and clean energies [48].

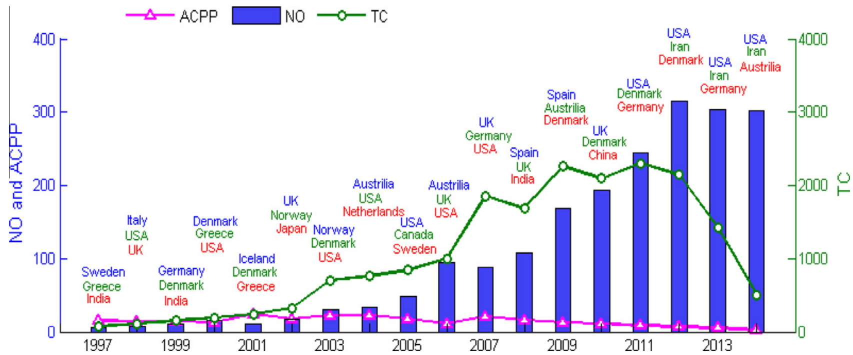

Fig. 2. Numbers of NO, TC and ACPP during the period of 1997–2014. Note: Countries in blue, green and red respectively correspond to the annual first, second and third largest published countries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the meantime, China released the "*Renewable Energy Law of the People's Republic of China*" to optimize its energy structure in February 2005 [49]. As a result, more studies on WPP have been published although the total amounts of published papers slightly reduced in 2013 and 2014. In general, the articles published in the last 9 years accounted for 91% of the total published articles. Also, the TC increased stably and reached the peak in 2011, while the ACPP had decreased during the period of 2007–2014. In addition, the annual top 3 publication countries include the U.S., Denmark, United Kingdom, Germany, Australia, Iran, Greece, Spain, Sweden, Norway, India, Italy, Iceland, Japan, Netherlands, Canada, and China. The U.S. has been the No. 1 productive country during the last four years while Iran has been the second, indicating their concerns on wind power price. However, with the largest wind power cumulative installation capacity, China only became the No. 3 productive country in 2010, reflecting that the Chinese scholars paid relatively less attention on such a topic.

3.2. Journals' performances

The collected 1994 articles were published in 857 different journals (or conference proceedings) indexed in Scopus. This indicates the diversified nature of publication distributions as well as the broad interests on WPP-related research. The top 20 journals, accounting for 31.41% of the total publications, are further analyzed in Table 1. Among all the journals, Energy Policy is the most influential journal with a number of 144 (7.25%) articles. Energy Policy is an international peer-reviewed journal addressing the policy implications of energy supply and use from economic, social, planning and environmental aspects. Papers cover global, regional, national, or even local topics that are of wider policy significance. Renewable and Sustainable Energy Reviews is the second influential journal which has a higher impact factor of 5.901 in 2014 and also mainly covers renewable and sustainable energy sources. The top 6 most influential journals are all key journals with higher impact factors, covering different aspects of energy research, such as policy, renewable energy, power and application, especially, the last three are all directly related with power. In addition, the top academic conference related with WPP is the international conference of IEEE Power and Energy Society General Meeting (PES). This conference provides the world's largest forum for sharing the latest technologies development in the electric power industry, and the key members of IEEE PES are also professional leaders in this field. Papers from the conference of IEEE PES appeared three times in the top 20 influential journals or conferences, indicating that it is the most important conference on WPP.

Table 1
The top 20 journals or related conferences.

Journals/conferences	TP[b]	%[c]	IF[d]
Energy Policy	144	7.25	2.575
Renewable and Sustainable Energy Reviews	65	3.27	5.901
Renewable Energy	60	3.02	3.476
IEEE Transactions on Power Systems	51	2.57	2.814
Energy	47	2.37	4.844
Applied Energy	35	1.76	5.613
IEEE Power and Energy Society General Meeting, PES 2012[a]	*24*	*1.21*	–
Energy Economics	24	1.21	2.708
IEEE Transactions on Sustainable Energy	20	1.01	3.656
Power	20	1.01	0.048
IEEE Transactions on Smart Grid	18	0.91	4.252
European Wind Energy Conference and Exhibition, EWEC 2010[a]	16	0.81	–
IEEE Power and Energy Society General Meeting, PES 2011[a]	*15*	*0.75*	–
International Journal of Hydrogen Energy	15	0.75	3.313
IEEE Power and Energy Society General Meeting, PES 2010[a]	*15*	*0.75*	–
Energy Conversion and Management	15	0.75	4.380
Wind Engineering	15	0.75	1.414
International Journal of Electrical Power and Energy Systems	12	0.60	3.432
IET Renewable Power Generation	12	0.60	1.904
Electric Power Systems Research	11	0.55	1.749

[a] Conferences or Meetings organized for specific research issues.
[b] The total publications in that journal during 1997–2014.
[c] The percentage of the related publications in that journal.
[d] The journal's impact factor for 2014.

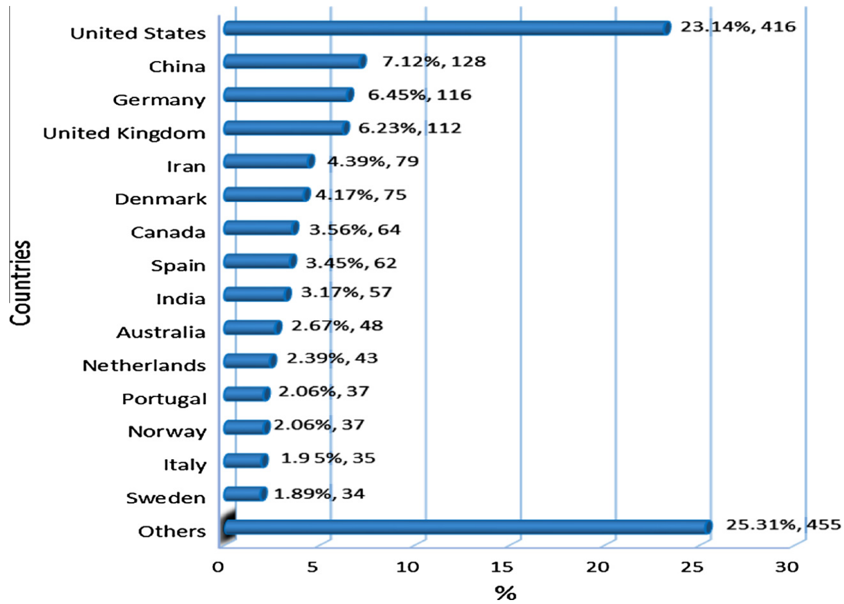

Fig. 3. The top 15 most productive countries.

3.3. Countries' characteristics

3.3.1. Countries' performances

The number of publications from one country reflects the attentions and overall strengths of this country in the related research fields. Fig. 3 shows the top 15 most productive countries under the situation that only the first author's nationality is considered. These top 15 countries published a total of 1343 articles, accounting for 74.69% of the total searched publications, including the U.S. (23.14%), China (7.12%), Germany (6.45%), United Kingdom (6.23%), Iran (4.39%), Denmark (4.17%), Canada (3.56%), Spain (3.45%), India (3.17%), Australia (2.67%), Netherlands (2.39%), Portugal (2.06%), Norway (2.06%), Italy (1.95%) and Sweden (1.89%), respectively. Also, these most productive countries have larger cumulative installed capacities (CICs) [50]. Among all the productive countries, the U.S. is the most productive, reflecting its leadership in the field of WPP. China ranked the 2nd although it has the largest cumulative installation wind power capacity in the world, reflecting that the Chinese academia needs to make more efforts. All the other countries in this list are the key countries on promoting wind power and therefore their academia have correspondingly made more contributions. Particularly, although Denmark is a small country, the Danish scholars have published 75 papers due to its highest wind power share in the total energy supply. Furthermore, among the top 15 most productive countries, 9 countries are from Europe, indicating that Europe is an active supporter of wind power.

3.3.2. Academic cooperation

Academic cooperation among different countries is of significance. On one hand, they can communicate with each other to enhance their understandings and seek innovative solutions. On the other hand, developing countries with backward technologies can learn advanced experiences from developed countries through international collaboration. Fig. 4 illustrates the academic collaborative relationships among various countries during the period of 1997–2014. It indicates that the top 10 countries with more international collaborations are the U.S, United Kingdom, Germany, Spain, Canada, China, Australia, Norway and Netherlands. The U.S scholars have published most co-authored papers with their partners in China, UK, Canada, Netherlands, Denmark and Australia. Major European countries, including Germany, UK, Denmark, Spain, have more mutual collaboration due to their geographical and culture proximity and active promotion of wind power. China is the top 1 Asian country in this field and the Chinese scholars have more collaboration activities with the U.S, UK, Australia, Hong Kong (as one region), and Singapore. As the key oil production countries in the Middle East, Saudi Arab, United Arab Emirates and Iran, have less international collaboration and less publications due to their strong dependence on oil export, less interests on promoting renewable and clean energy, and also maybe academic culture.

Although the U.S has led the international academic cooperation on WPP, other countries, such as China, Denmark, Germany, Spain, United Kingdom and Japan, should further collaborate each other so that more productive and innovative research outcomes can be presented. For example, in the year of 2014, China's cumulative wind power installed capacity and generation reached 97 GW and 1599 TW h, respectively, but facing several problems such as large-scale utilization and higher prices. Denmark's cumulative installed capacity and generation were 5 GW and 131 TW h, respectively, with the application of advanced technologies. However, less academic cooperation between China and Denmark was conducted. Therefore, it is critical to further promote academic collaboration between China and leading European countries (such as Denmark) so that more technology transfers can occur. In this regard, research funding agencies from different countries should work together to provide more joint research opportunities.

3.4. Institutions' performances

Table 2 lists the performances of the top 15 productive institutions. Among all of them, 6 institutions locate in the U.S., indicating that the American research institutions (including both universities and research institutes) are more active in such a field than other countries. It is not surprised to see that the Technical University of Denmark ranked the 1st in this table since Denmark is the No. 1 country in terms of the share of wind power in the overall energy supply. The North China Electric Power University is the only one from China and ranked the second productive institution in the world. Another institution from developing world is the

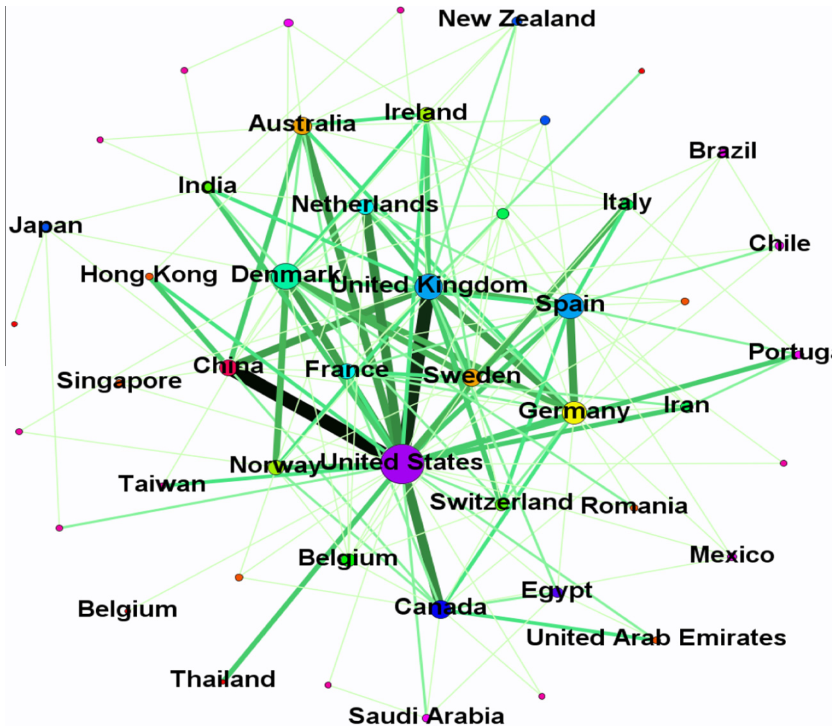

Fig. 4. The academic collaborative relationships among 49 countries. Note: One line between two countries means that they have cooperation relationship in this field. The thicker the line is, the stronger the collaboration is. The node size is determined by that country's total collaborative articles.

Table 2
The top 15 most productive institutions on WPP during the period of 1997–2014.

Rank	Institutions	Country	Articles
1	Technical University of Denmark	Denmark	42
2	North China Electric Power University	China	26
3	Islamic Azad University	Iran	26
4	Aalborg University	Denmark	26
5	Carnegie Mellon University	USA	23
6	IEEE	–	23
7	National Renewable Energy Laboratory	USA	22
8	University of Waterloo	Canada	18
9	Stanford University	USA	16
10	University of California	USA	16
11	Argonne National Laboratory	USA	16
12	Cornell University	USA	16
13	University College Dublin	Ireland	16
14	University of New South Wales	Australia	15
15	Norwegian University of Science and Technology	Norway	15

Islamic Azad University in Iran, indicating that the developing world need to further support the related studies.

3.5. The most cited articles

In this section, the evolution characteristics of the top 2 cited articles in each year are explored. Furthermore, the academic co-citing network among the top 60 cited articles during the period of 1997–2014 is also analyzed.

In terms of articles, the citation counts determine their academic values. The changes of annual citations can help track the impact of one published article. Usually, citation rates are heavily dependent on the disciplines and the number of people working in that area. Particularly, review papers received more citations than regular research papers because they summarize results from many papers. Figs. 5 and 6 illustrate the evolution trends of the first and second most cited articles (with key words for each article) related with WPP in each year during the period of 2001–2014. It is clear that the citation counts for most high quality papers reached the peak within five years of their publication, mainly due to fast academic development. For instance, the citation counts for the most cited article published in 2001 experienced increasing citations (see Fig. 5) since it reviews the global use of geothermal energy and compares the electricity costs with other renewable energies [51]. Another key feature is that the second most cited articles are more relevant with WPP than the most cited articles according to the keywords. In general, the most cited article focuses on WPP more from the perspective of hybrid renewable electricity system, while the second most cited article focuses on the cost-benefit analysis of wind power. It demonstrates it is crucial to consider the integrated regulation of different power sources, such as wind power, hydro-power, and coal-burning based power. At the same time, higher costs must eventually be alleviated through higher wind power sale prices. In this regard, technology learning curves can be used as an effective analytical tool. In addition, the most cited article published in 2008 experienced the fastest citation counts growth. The keywords of this article include Day-ahead electricity markets, Energy storage, Optimization, Profit maximum, and Wind power. This article investigated the combined optimization of a wind farm and a pumped-storage facility by developing an optimization model, which was formulated as a two-stage stochastic programming problem with two random parameters: market prices and wind generation [52].

The top 2 most cited articles related with WPP in each year are illustrated in Figs. 5 and 6. However, both figures do not present the complete picture on citation records. For example, the citation counts of the first most cited article published in 2000 was less than that of the third most cited article published in 2009. Thus, a further citing analysis for the top 60 articles (with over 65 citation counts) published during 1997–2014 is necessary (see Fig. 7). The top 60 cited articles can cover the most important issues related with WPP and the co-citing intensity can reflect their

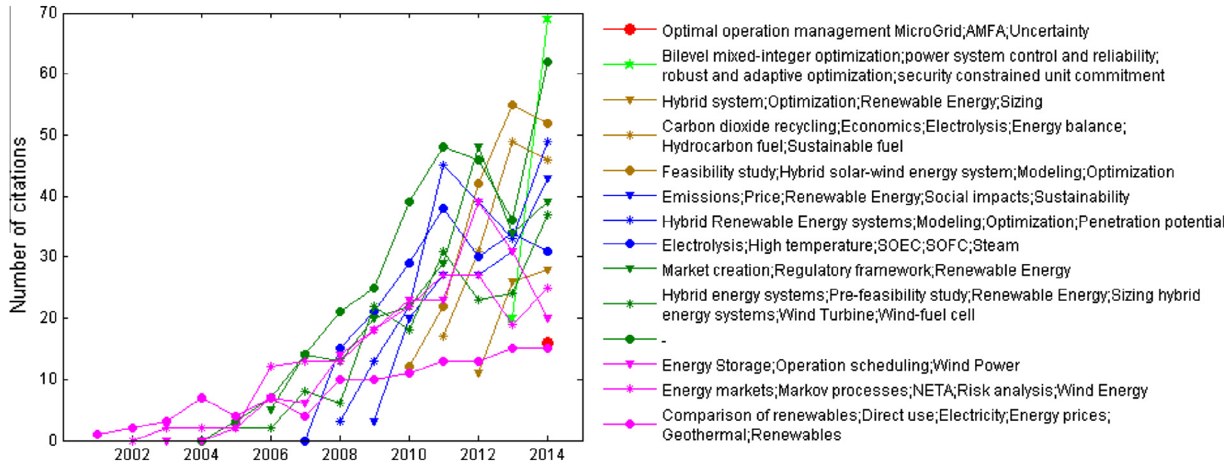

Fig. 5. The most cited articles in each year and their corresponding citation evolution.

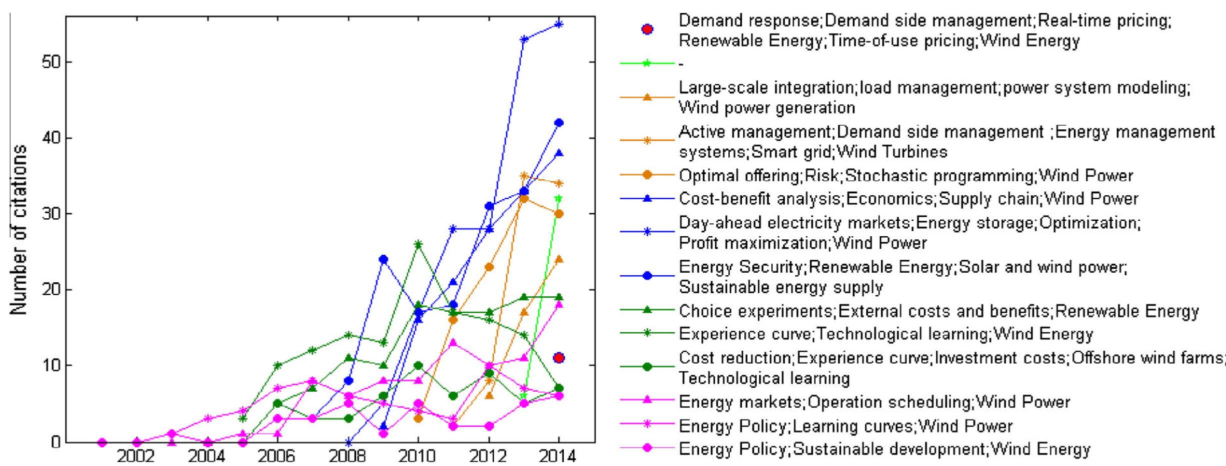

Fig. 6. The second most cited articles in each year and their corresponding citation evolution.

relationships. Co-citing intensity between two articles is represented by the number of the same reference. The more same references the two articles have, the more similar their research contents are.

It is clear that many real networks exhibit a concentration of links within certain groups of nodes called communities (or clusters). The detection of the community structure of a given network could help discover some hidden features of its topological architecture [47]. Fig. 7 illustrates that 4 communities have significant collaboration in the academic co-citing network according to their co-citing intensity relationships. The most remarkable community is dominated by Zhou., Nema., Erdinc., and Deshmukh, with 11co-authored articles, focusing on modeling and optimization for hybrid energy system. The second productive community focuses on cost and risk assessment on WPP and raised several relevant policy implications. The other two productive communities also have their unique research fields, e.g., community 3 studies storage and management of wind integration, community 4 highlights energy security and sustainability.

In general, diversified studies have been published in such a research field. However, most of them still focus on cost, risk, carbon emission reduction and environmental efficiency, the key areas related with WPP. In this regard, more integrated study need to be conducted, such as a hybrid model considering various factors.

3.6. Research hot points

3.6.1. Keywords' performances

Among 1994 articles, 1460 articles provided a total of 6937 keywords (3359 categories), accounting for 73.37% of total articles. There are on average five keywords for each article. In order to identify the research focus on WPP, keywords analysis is conducted. Fig. 8 illustrates the frequency of keywords and their ranks, following the power law distribution. It is clear that most keywords were seldom used and several keywords were frequently used. In this regard, 2599 keywords only appeared once, accounting for 77.37% of the entire 3359 keywords. However, the top 4 (0.12%) most used keywords appeared 950 times, including renewable energy (289 times), wind power (281 times), wind energy (224 times), and electricity markets (156 times). Other keywords with more than 50 times appearance include day-ahead electricity market, optimization, wind turbine, energy storage, demand response and electric vehicles.

One research article usually includes research subjects, purposes, methods, and research fields. Due to this reason, all the keywords are classified into these four types. Fig. 8 shows the classification of 3180 keywords (accounting for 45.84% of the total keywords) in WPP, while the rest keywords are excluded due to data unavailability and lower appearance frequencies. These 3180 keywords are further classified into five categories.

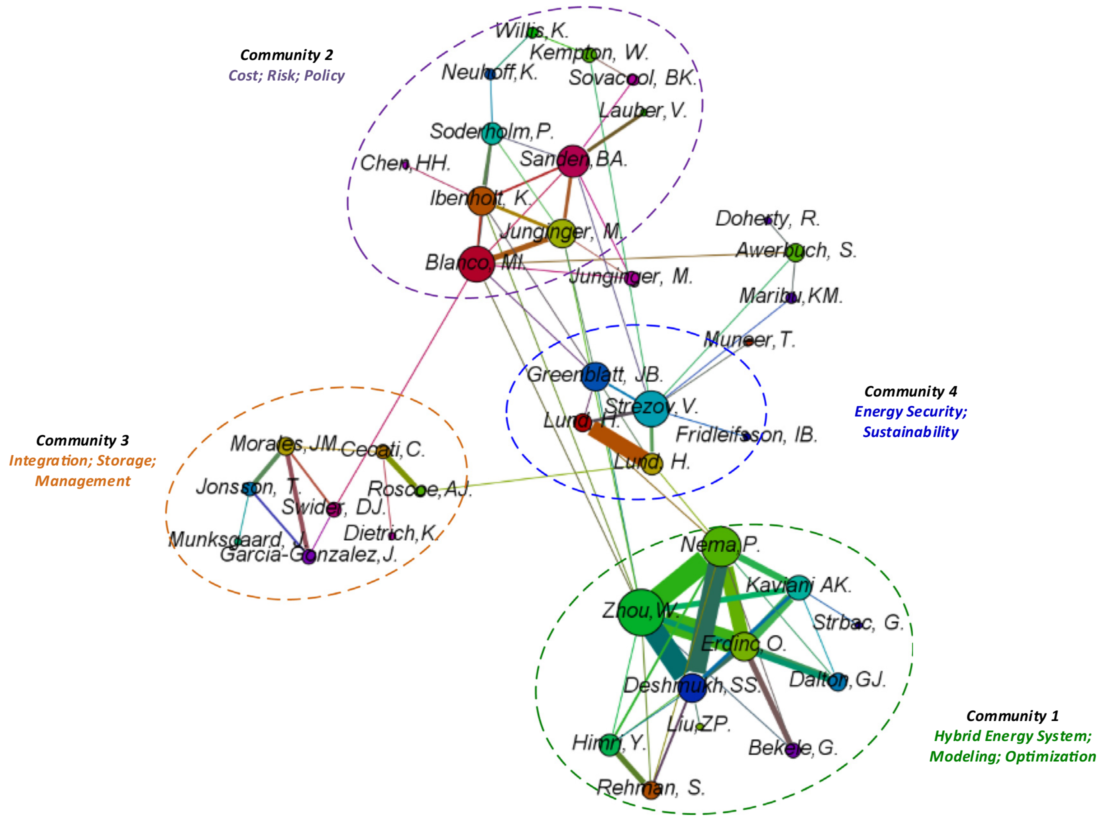

Fig. 7. The academic co-citing network among top 60 cited articles during 1997–2014. Note: The node size is determined by that article's total citations. The line between two articles means that they have at least one same reference. The thicker the line is, the stronger the correlation is.

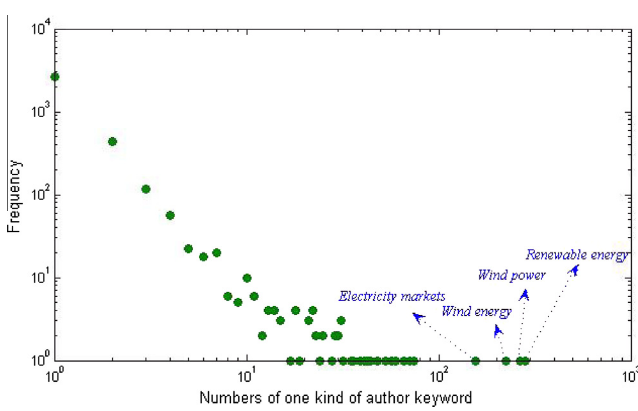

Fig. 8. The power distribution between the frequencies and ranks of keywords.

The first two categories refer to research subjects of WPP. Subject 1 refers to different types of energy resource, including renewable energy, electricity, wind energy, solar energy and hydro energy. In terms of wind energy, it is further divided into wind generation, wind farm, wind turbine, offshore wind, etc. Among them, wind energy is the most important subject, with an appearance percentage of 43.1%. Subject 2 refers to electricity market types, including distributed power generation, smart grid, demand response, small scaled grid, electric vehicles, wind power integration and day-ahead electricity market.

In terms of methods, the most adopted keywords are optimization, programming, forecasting, and simulations (see Fig. 9). Major optimization methods include stochastic optimization, multi-objective optimization, and dynamic optimization, aiming to find the optimal solutions for the setup objectives given a set of constraints. These methods can help identify the best bidding strategies for producers in the day-ahead market and analyze the merit order effect of wind power penetration [53,54]. Programming methods include linear, integer and dynamic programming, which represents different algorithms to solve the problem of optimization. Forecasting mainly focuses on short-term wind speeds, loads, and electricity prices since these factors are closely related to wind power pricing. Simulations can help predict the possible cost effectiveness and environmental impacts to wind farm, micro grid, electricity market and hybrid system. The most used simulation method is the famous Monte Carlo simulation [55]. Other popular methods include learning curves (15), conditional value at risk (8), genetic algorithm (15), neural network (3), and game theory (4) although they are not frequently used, marked as "Others" in Fig. 9. In general, Fig. 9 demonstrates the most popular methods related with WPP so that researchers can better recognize the most useful ones.

The major research fields of WPP include cost, storage, economic benefit, risk or uncertainty, climate change and price (see Fig. 9). In terms of price (33.7%), it is further divided into electricity price, bidding strategy, real time pricing, etc. Electricity price is the most important research field, while keywords of bidding strategy, real time pricing, and feed-in tariff occupy have less frequency. However, less attention has been paid on the emerging field of smart grid. Consequently, it is critical for academia to strengthen the studies related with smart grid so that appropriate policies can be raised for improving the absorptive capacity of wind power to the smart grid system.

3.6.2. Future research directions

While wind power price studies have made significant progress in recent years, many challenges still exist. Fig. 2 indicates that NO

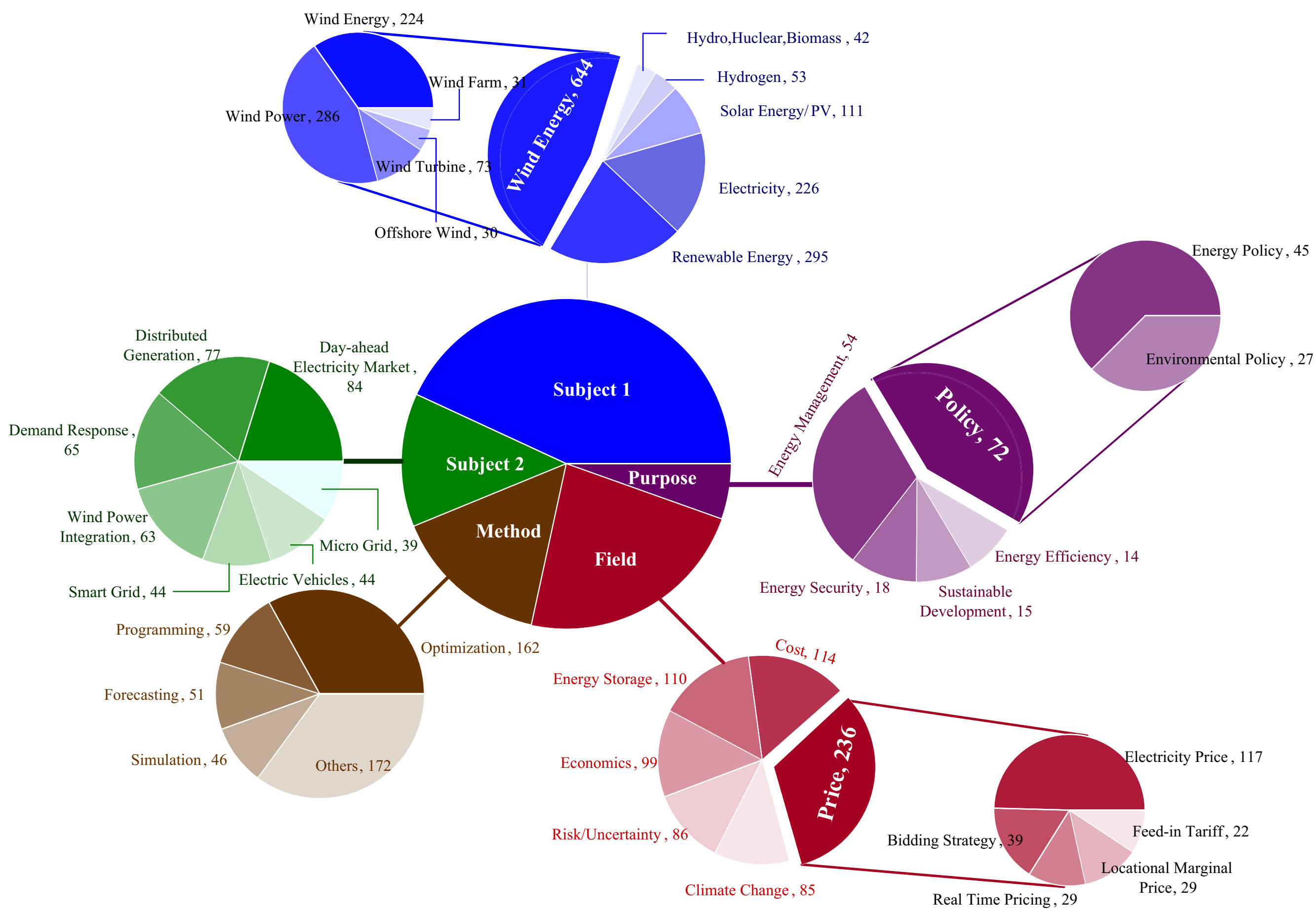

Fig. 9. Distributions of keywords.

experienced substantial increases in years of 2006 and 2012 due to the meeting of G7 countries and significant adjustment of renewable energy policies, respectively. This reflects that the research interests coincide with international renewable energy policy changes. Based on the above analysis results and wind power plans in different countries, we propose future WPP research directions in the below five aspects.

First, changes of international renewable energy policies determine future research direction of WPP-related research. Since 2011, countries with wide application of wind power, such as Germany, the U.S., France, United Kingdom, Denmark, and China, have released many renewable energy policies, such as renewable energy acts, key funds for renewable energy investment plan, and the renewable energy roadmaps, inducing future requirements on smart grids, renewable energy technologies, wind power grid connection and offshore wind power generation. Especially, since the rapid development of smart grids can further facilitate the connection of wind power with conventional power grids, such a topic will become the next hot issue. For instance, how to solve the deviation between frequency and voltage caused by wind power output fluctuation in a more secure way is a crucial issue. Essentially, future research on WPP should focus on large-scale wind energy generation and smart grid access technologies so that current technology limitations can be removed. Also, it is rational to establish a market-oriented pricing mechanism so that incentive policies can be prepared to promote the connection of wind power with current power grids. In addition, it is necessary to promote the integration of different power sources, such as wind power, hydro-power and coal-burning based power. In this regard, more studies should focus on establishing a complimentary power system between wind power and hydro-power and between wind power and solar power so that the negative impact of wind power can be offset. Finally, higher installed costs should eventually be alleviated through higher wind power sale prices. In order to achieve similar costs to other energies, technical innovation on wind power should be supported. In this regard, learning curves can be used as one analytical tool for technology forecasting so that assumptions over a range of key uncertainties can be examined.

Second, offshore wind power has an enormous potential. The weaknesses for land based wind power include unbalanced wind resource distributions, large land occupation, and negative impacts to biodiversity protection. These disadvantages can be avoided by the application of offshore wind power. However, current studies on the promotion and application of offshore wind power generation are still limited according to Fig. 9. Therefore, more studies are needed in this regard, such as advanced offshore wind power technologies, cost-benefit analysis of such projects, reasonable prices, market access criteria, and maintenance and repair issues.

Third, China dominates wind power application in the world and has significant impact on global wind power markets. China's wind power depression during the period of 2012–2013 led to the global depression. But its revitalization in the year of 2014 helped recover the global wind market. Consequently, China's wind power sector deserves more investigations. Possible topics include the feasibility of its wind energy generation technologies, appropriate prices, suitable subsidies, relevant big data analysis, and rational distribution of wind power across the whole country.

Fourth, it is critical to strengthen technologies exchanges and cooperation among different countries. Although the U.S. has led the international academic cooperation research on WPP, other countries, such as China, Denmark, Germany, Spain, United Kingdom and Japan, should further collaborate each other so that more productive and innovative research outcomes can be learned or shared. In this regard, research funding agencies from different countries should cooperate together to jointly release research funds by addressing common research topics. Without adequate research funds, such an initiative will not be easily realized.

Fifth, WPP related studies are more interdisciplinary since it involves in different disciplines. The investigation of this research field has already uncovered that optimization, dynamic planning and forecasting are the main methods on WPP. Therefore, it will be rational for more researchers to engage in this research area by further employing these methods. Especially, the innovative combination of different methods, tools and data can help solve more specific problems by addressing more factors, such as costs, risk/uncertainty assessment, carbon emission reduction and eco-efficiency of WPP-related projects.

4. Conclusions

With fast development of wind power sector, more academic efforts have been made in the field of WPP. However, comprehensive reviews on such a topic are still less, leading to more specific research requests. Under such a circumstance, this study fills such a research gap by reviewing the current status of WPP through both bibliometric analysis and complex network analysis. It provides a complete picture on WPP and points out future research directions. The bibliometric analysis uncovers that the total number of WPP related publications had stably increased during 1997–2005 and then experienced fast increases after 2006. Total papers published in the last 9 years accounted for 91% of the total published papers and were dominated by the U.S. and Iran in the last 3 years. These papers were published in a total of 857 kinds of journals, indicating that such a field has been studied under diversified topics and from various perspectives. Energy Policy is the most influential journal while IEEE Power and Energy Society General Meeting is the most influential international conference. Also, China has the largest wind power installation capacity, but with fewer articles. The most productive countries always have more cooperative publications, except for China and Iran. With regard to institutions, many productive institutions are from the U.S. Technical University of Denmark ranked the 1st with respect to the total publications, while the North China Electric Power University is the only one from China. In terms of the most cited articles, the first most cited article focuses on WPP from the perspective of renewable electricity while the second one mainly focused on the cost-benefit analysis of wind power. Finally, future research directions are presented based upon such bibliometric analysis, including large-scale wind energy generation and smart grid access technologies, offshore wind power, more China-related studies, technologies exchanges and cooperation among different countries, enhancement of international cooperation.

This study is expected to benefit researchers in shaping their future research directions so that they can receive more innovative ideas and understand the most relevant journals. Also, the results can provide valuable policy insights to those practitioners so that they are able to know the most famous experts in such a field and get more accurate consulting service for their decision-making.

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