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How Solar and Wind Powers can Complement Each Other in Spatial-Temporal Dimensions? - An Empirical Study in China's Hubei Province

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Abstract – *This paper measured the total solar radiation and wind power density by adopting climatological methods using 2014 – 2016 monthly mean data of sunshine and wind speed in 17 cities of Hubei province in China, and then analyzed the spatial and temporal complementarity of solar and wind powers in these cities in Hubei province using the ArcGIS software. The results indicate that: (1) the spatial distribution of the solar energy resources in Hubei features high in the northeast and low in the southwest, with distinct divisions of the four seasons; The total annual solar radiation across the province is between 4055.87 and 5078.37 MJ/m^2, with the most solar radiation appears in summer, followed by spring and autumn, and the least being in winter; (2) the wind energy resources in Hubei has the characteristic of high in the middle eastern region and low in the west, with the seasonal trend of strong in spring and summer, mild in winter, and weak in autumn; (3) the solar and wind energy resources in Hubei are complementary highly in space and slightly in season. Finally, this paper proposes relevant policy recommendations based on these findings.*

Keywords – ArcGIS, Hubei province, spatial-temporal complementarity, solar energy, wind energy.

1. INTRODUCTION

With the increasing global energy shortages and environmental concerns, the development and utilization of renewable and clean energy is getting urgent. According to China's yearbook statistics for new energy and renewable energy, China has a total solar energy resource equivalent to 170Mtoc, with the power generation potential of 1381780 MkWh. By the end of 2014, China has installed 76,241 wind power generators with accumulative installed capacity of 114609MW (China Wind Energy Association, 2015). In order to promote the rapid development of renewable energy such as solar energy and wind energy, the Chinese government has issued a series of policies. China's Energy Development Strategy Action Plan (2014-2020) pointed out that by 2020, the wind power installed capacity will reach 200 million kilowatts, and photovoltaic installed capacity 100 million kilowatts in China.

Hubei province is located at 29°01′-33°6′47″ North latitude and 108°21′-116°07′ East longitude, featuring a subtropical climate. It is surrounded by mountains in the east, west and north, with low-lying land in the middle. It is an incomplete basin opening slightly to the south. Of the total area of Hubei province, mountains account for 56%, hills 24%, and plains and lakes 20%. According to the meteorological statistics, Hubei has sufficient solar radiation during March-October, with the annual solar radiation of 85-114 kcal/cm^2 in most areas, and the average sunshine ranges 1100-2150 hours a year.

It is a fundamentally important work to estimate solar, wind energy resources and their spatial distributions by adopting scientific methodologies, which is the key step to developing a large-scale solar PV power generation and wind power generation industry. To date, some scholars have studied on the distribution of solar and wind energy resources by using GIS for specific regions such as Urumqi, Nanjing and so on, predicting the potentials for the future utilization.

Research literature in this field mainly includes the following three aspects:

1.1 Research on Solar Photovoltaic (PV) Power Generation

There are scholars who have carried out the research on the distribution and reserves of solar energy resources. Liu [1] determined the parameters of the calculation formula of the total solar radiation in Hubei province using OLS, and analyzed the temporal and spatial distribution characteristics of solar energy in Hubei province combined with sunshine hours, sunny days, cloudy days and other meteorological data. Mubiru *et al.* [2] assessed the distributions of the monthly means of hourly total, diffuse and direct solar irradiation at a selected site in the equatorial region. Park *et al.* [3] developed an empirical model which estimated solar radiation from sunshine duration data to analyze the distribution of solar energy over South Korea. Janjai *et al.* [4] and Jin *et al.* [5] both calculated the total solar radiation of a region. Qian [6] studied the total solar radiation in the eastern Hexi corridor in the past 30 years by linear regression and linear correlation.

Other scholars have analyzed the potential of solar photovoltaic power generation. Shen [7] evaluated the potential of the development and utilization of solar energy in mainland of China comprehensively by using AHP method. Sun *et al.* [8] evaluated the

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comprehensive potential analysis of solar PV generation at the regional scale based on GIS. Sang *et al.* [9], Li [10] analyzed the development potential of the solar energy resources in Ningxia and China respectively by factor analysis. Liu *et al.* [11] assessed the available solar energy resources of Jiangsu residents' building roofs by establishing an evaluation model combined with the roof areas. Hachem *et al.* [12] investigated the geometric form effects on solar potential of housing units. Man *et al.* [13] studied on the use of Remote Sensing (RS) technologies and Geographic Information Systems (GIS) for estimation of city-wide photovoltaic (PV) potential in Hong Kong. Li *et al.* [14] constructed a pixel-based methodology for estimating solar energy potential over roofs. Castillo *et al.* [15] generated a suitability map for photovoltaic (PV) power plants across the European Union at high spatial resolution using a multi-criteria assessment (MCA) supported by Geographical Information System (GIS) to assess the potential of solar power generation in European regions. Huld *et al.* [16] evaluated the utilization potential of solar energy in the EU through developing a PVGIS system based on solar radiation and ambient temperature data. Olatomiwa *et al.* [17] and Lazzaroni *et al.* [18] both used the support vector model to evaluate the potential of solar energy resources. Yadav *et al.* [19] forecasted and evaluated the potential of solar energy in Himachal Pradesh of Indian by the artificial neural network model.

1.2 Research on Wind Power Generation

So far, some scholars have conducted studies on the distribution and potential of wind energy resources. Zhang *et al.* [20] studied the wind energy and distribution of Henan province by ArcGIS using statistical method and hydrodynamic method. Kim *et al.* [21] analyzed the wind distribution over the Korean Peninsula using numerically optimized wind data. Zhang *et al.* [22] made a numerical simulation of high spatial resolution to the wind energy resources of Hubei province using a mesoscale meteorological model WRF. Shu *et al.* [23] presented a statistical analysis of the wind characteristics and wind energy potential at typical sites in Hong Kong by the assistance of Weibull distribution model. Li and Li [24] examined the wind characteristics such as annual, seasonal, monthly and diurnal wind speed variations and wind direction variations for the Waterloo region in Canada and quantified the available wind energy potential in this area. Florin and Eugen [25] assessed the wind energy potential using a classical logarithmic transformation law and evaluated the seasonal and spatial distributions of the wind energy. Zhang *et al.* [26] used a more comprehensive metric: the wind power potential (WPP) which used a joint distribution of wind speed and direction to characterize the stochastic variation of wind conditions. Li [27] evaluated and analyzed the development potential of 10m high wind energy resources in China using a comprehensive index. Sun *et al.* [28] assessed the development potential of land wind energy resources in Fujian province by using GIS. Cheng *et al.* [29] analyzed the restriction factors of the development of land wind energy taking the Jiuquan wind power base of Gansu as an example. Adaramola and Oyewola [30] analyzed the wind speed distribution and wind energy availability in Nigeria and discussed the potential of this resource for generating wind power in the country. Bataineh and Dalalah [31] assessed wind power potential for seven locations in Jordan using statistical analysis to determine the wind characteristic based on the measured wind data. Akpinar and Akpinar [32] investigated an analysis of wind characteristics of four stations over a period of 8 years (1998-2005) and estimated the potential of wind energy using finite mixture distribution models. Adaramola *et al.* [33] examined the wind energy potential and the economic viability of using wind turbine for electricity generation in selected locations along the coastal region of Ghana using the two-parameter Weibull probability density function. Dabbaghiyan *et al.* [34] assessed the wind energy potential for four locations in Bushehr province of Iran using the Weibull probability distribution function. Wang *et al.* [35] assessed the potential of wind energy and forecasted the wind speed in four locations in China based on the data pre-processing technique and swarm intelligent optimization algorithms. Khahro *et al.* [36] and Mohammadi *et al.* [37] calculated the wind energy density using Weibull parameter estimation methods.

Others have done researches on wind farm location and wind energy forecasting. Wang *et al.* [38] made a feasibility study of the macro-siting of a development project for wind energy utilization. Zaunbrecher *et al.* [39] undertook a comparison of siting preferences for electricity pylons and wind power plants by applying conjoint analyses. Liljenfeldt *et al.* [40] investigated possible relationships between decisions on proposed windmill sites in Sweden and the socio-economic characteristics of people living in these areas. Sun *et al.* [41] presented an optimal day-ahead wind-thermal generation scheduling method that predicted features of wind speeds and analyzed the historical wind statistics of wind resources according to the statistical results and wind prediction. Frías-Paredes *et al.* [42] defined a new method to match time series in order to assess energy forecasting accuracy and demonstrate the significant progress in the analysis and prediction model tasks by evaluating the prediction accuracy of wind energy. Taylor [43] developed a multinomial logit formulation to model jointly the probability of ramp events at more than one wind farm and evaluated post-sample probability forecast accuracy using hourly wind power data from four wind farms.

1.3 Research on the Complementarity between Solar and Wind Powers

To date, there is limited literature targeting the combination of solar and wind energies. Ye *et al.* [44] applied the hybrid optimization model for multiple energy resources and loaded types to analyze the feasibility of satisfying energy demand and applied its synergy model to a 2.8 km (2) isolated island in the South China Sea. The simulation results demonstrated that solar and wind energy combined with appropriate energy storage equipment can meet the energy demand of the island. Ji *et al.* [45] proposed a novel hybrid wind-solar-compressed air energy storage (WS-CAES) system, which can store unstable wind and solar power for a stable output of electric energy and hot water to solve some power grid management problems owing to their nature of fluctuation and intermittency. Gui [46], Chen [47] studied on the solar and wind energy storage, seeking a breakthrough on the problem of new energy storage from a technological perspective. Liu *et al.* [48] analyzed the storage of regional wind energy resources in Shanxi province based on the data of monthly average wind speed in 11 cities (counties), and then studied on the complementarity of the total solar radiation on the inclined surface of the best angle and wind energy storage in these areas, providing an important theoretical basis for the development and utilization of a wind-solar complementary power generation system of Shanxi. Colantoni *et al.* [49] presented a mathematical model, which can record solar radiation distribution and cumulative wind speed, for outlining future insights and potentials of hybrid photovoltaic/wind installations throughout the Tunisian territory. Ferrer-Martí *et al.* [50] presented a mathematical programming model to optimize the design of hybrid wind-PV systems that solved the location of the wind-PV generators and the design of the microgrids, taking into account the demand of the consumption points and the energy potential.

Nnadi *et al.* [51] proposed a hybrid solar-wind generation system that can improve the standard of living. Shi *et al.* [52] proposed a novel method for optimizing the techno - economic performance of the PV- wind power system arrangements. The results showed that the techno- economic performance of the PV - wind power system was superior to that of the pure PV power system or the pure wind power system because of the compatible properties of solar resource and wind resource. Vick *et al.* [53] indicated that an UV (ultraviolet) water purification system, combining the wind and the solar system together would be more reliable than either one alone. Madholopa *et al.* [54], Cheng *et al.* [55] had done a study on a hybrid generator system for solar and wind powers, and explored the design and practical operations for a hybrid generator system. Esteban *et al.* [56] proposed a method and carried out a simulation to show how much energy could be produced for a solar-wind renewable energy system. Gong *et al.* [57] analyzed the temporal and spatial distribution of wind energy and solar energy resources in Liaoning province using meteorological data and wind power field data and made a preliminary zoning. Liu *et al.* [58] analyzed the spatial and temporal (month, day, hour) complementarity of wind and solar powers of a virtual power plant in different scenarios, and found that solar and wind energy resources was highly complementary in the time dimension. Zhao [59] analyzed the potential and design of a wind-solar complementary power generation system in Henan province of China. Santosalamillos *et al.* [60] explored the use of canonical correlation analysis (CCA) for analyzing spatiotemporal balancing between regional solar and wind energy resources.

Current related researches mainly focused on: (1) the distribution and potential of the resources, using ArcGIS dominate by a single resource (either solar or wind resource) and concentrating on larger regions (the China nationwide, Northwest area or the northeast of China etc.), and some regions with relatively abundant solar or wind energy resources such as Ningxia, Qinghai, Inner Mongolia, and so on; (2) the engineering and technology development for the wind and solar complementation, such as the development for hybrid power generation systems and energy storage problems. There are also some scholars who analyze the complementarity of solar and wind energy in specific regions.

Nevertheless, independent wind or solar power systems cannot provide stable and reliable power supplies. The strong spatial and temporal complementarity of wind energy and solar energy can weaken or eliminate the weakness of this poor stability. The main reason for the slow popularization and application of solar and wind complementary power generation systems in the past is the high price of solar cells and inefficiency of power generation. In recent years, with the continuous progress of technology and industrial scale expansion, the quality of photovoltaic cells and power generation efficiency has improved and the costs have dropped significantly. Moreover, the complementation of solar energy and wind energy is also beneficial to protecting the storage battery and reducing the damage possibility of the battery due to power loss. With the development of society and the improvement of people's living standards, the number of electrical equipment used is increasing rapidly, and the consumption of electricity is increasing. Since the quality of power supply is raised, the original single wind power and photovoltaic power generation has been unable to meet the majority of farmers and fishermen's needs. There is an urgent need for a power system with larger capacity, more reliability and cost effectiveness. Existing literature review shows that the research in this field is still very weak, with the lack of studies on the spatial distribution of wind and solar energy resources in Hubei province, where is the heartland and bread basket of China; and the studies on both the temporal and spatial complementarity of the solar energy and wind energy are also very limited. Therefore, it is of great theoretical and practical significance to study on the complementarity of solar energy and wind energy of Hubei province from spatial and temporal aspects.

To fill in this gap, the authors calculated the solar energy and wind energy resource reserves using the meteorological data (monthly average data) of Hubei province based on the classical formula of climatology and analyzed the changing characteristics of the solar energy and wind energy from regional and seasonal aspects. With the spatial complementarity index for the first time and combined with ArcGIS technology, the authors analyzed the complementarity of solar energy and wind energy from spatial and temporal aspects. This paper intends to answer the following questions: What are the solar and wind energy reserves of Hubei province? What is the distribution of solar and wind energy from spatial and temporal aspects? Whether the solar and wind energy is complementary to each other? What is the degree of the complementarity? These problems are of great significance for the rational development of solar energy and wind energy resources in Hubei province. The framework of this paper is shown in Figure 1.

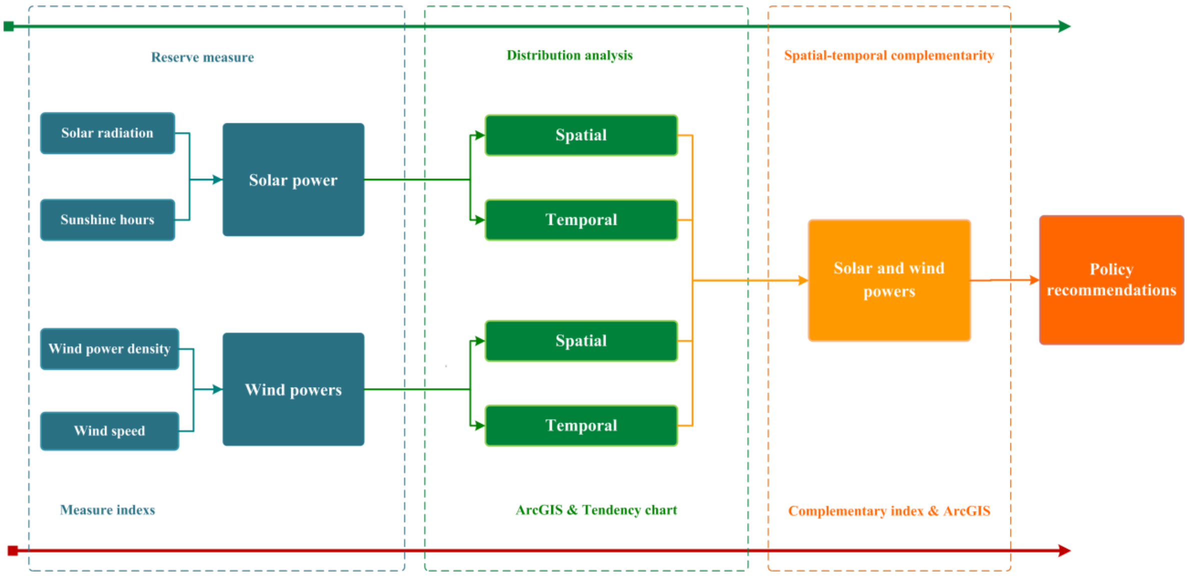

Fig. 1.The framework of this paper.

2. RESEARCH METHODOLOGIES AND DATA

2.1 Calculation Methods for Solar Radiation

This paper analyses the solar energy resources availability of Hubei province based on sunshine hours and solar radiation reaching the ground, which are the main parameters characterizing solar energy resources. In the 17 regional meteorological stations in Hubei province selected by this study, the solar radiation observation data are only available for Wuhan and Yichang, and the data for the rest of 15 regions are calculated using the climatology methods. At present, there are many climatological methods for estimating solar radiation in the academia. For this study, the authors adopted astronomical radiation methods with the following formula:

$$Q = Q_O(a + b * S) \tag{1}$$

where, S is the percentage of sunshine, Q is the total solar radiation, Q_0 is the astronomical radiation, a and b are empirical coefficients. Using the results measured by the Regional Planning Office of Agricultural Climate of the Hubei Provincial Meteorological Bureau, a takes 0.19, and b takes 0.55 [61].

In terms of the monthly astronomical radiation, the authors adopted literature [62] formula, calculated the daily radiation and aggregated to the monthly value.

$$Q_r = \frac{1440}{\pi} I_O \rho(\omega_O \sin\varphi\sin\delta + \cos\varphi\cos\delta\sin\omega_o) \tag{2}$$

where, Q_r is the daily astronomical radiation (unit: MJ/m^2d), I_o is the solar constant, I_o = 0.0820 (unit: MJ/m^2d); ρ is the reciprocal of solar-terrestrial relative distance.

$$\rho = 1 + 0.033\cos\left(\frac{2\pi}{365}T\right) \tag{3}$$

where, δ is the solar declination (rad)

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \tag{4}$$

where, J is the calculation date in the order of the year, January 1st is 1, with the values ranging from 1 to 365 or 366; is the sunset hour angle (rad).

$$\omega_O = \cos^{-1}(-\tan\varphi\tan\delta) \tag{5}$$

where, φ is the latitude (rad).

2.2 Calculation Methods for Wind Energy

The available wind energy density (wind power density) is used to measure the volume of a region's wind energy resources. Wind energy density is the wind energy that vertically flows through the unit area in a given time period [48]. The formula is:

$$P = \frac{1}{2}\rho v^3 \tag{6}$$

where, the unit of wind energy density P is W/m^{-2}, ρ is the air density kg/m^3, v is the wind speed (m/s).

Air density ρ can be calculated by the following formula [63]:

$$\rho = [1.276/(1 + 0.00336T)] \times [(P - 0.378e)/1000] \tag{7}$$

where, P is the monthly average atmospheric pressure, with the unit of hPa; T is the monthly average temperature, with the unit of centigrade (°C); e is the absolute humidity, with the unit of hPa; Taking the unit cross-sectional area F = 1, the authors can calculate the wind energy of that unit cross-sectional area in a given time.

For the determination of the absolute humidity, in this study the authors converted the relative humidity to absolute humidity referencing to relevant literature [64]. The formula is:

$$Relative\ Humidity = \frac{Vapor\ Press\ (Absolute\ Humidity)}{Saturation\ Vapor\ Press} * 100, \%$$

$$Vapor\ Press\ (Absolute\ Humidity) = Relative\ Humidity * Saturation\ Vapor\ Press \quad (8)$$

Saturation vapor pressure uses the Goff-Gratch formula recommended by the World Meteorological Organization. The formula of pure horizontal surface saturation vapor pressure is:

$$\log E_w = 10.79574(1 - T_1/T) - 5.02800\log(T/T_1) + 1.50475 \times 10^{-4}\left[1 - 10^{-82969(T/T_1 - 1)}\right] + 0.42873 \times 10^{-3}\left[10^{4.76955(1 - T/T_1)} - 1\right] + 0.78614 \quad (9)$$

where, T_1= 273.16 (the triple point thermodynamic temperature of water, with the unit of K), T = 273.15 + t°C (thermodynamic temperature, with the unit of K).

2.3 The Definition of Complementary Index

The ratio between the difference of the total reserves of solar and wind resources was defined as the complementary index of the two. The greater the ratio is, the stronger the complementarity of the two. Specific calculation formula is as follows:

$$r = \frac{|Solar\ energyresource\ resrves - Wind\ energy\ resource\ reserves|}{Solar\ energy\ resource\ reserves + Wind\ energy\ resource\ reserves} \quad (10)$$

Referencing the division of correlations of the two variables in statistics, complementarity between solar and wind powers can be divided into several ways: when $r \geq 0.8$, it can be regarded as highly complementarity; when $0.5 \leq r < 0.8$, it can be seen as moderate complementarity; when $0.3 \leq r < 0.5$, it can be said of low complementarity; when $r < 0.3$, the complementarity between the two is extremely weak, and it can be regarded as no complementarity.

2.4 Data Sources

In this study, the following data was used: 2014-2016 monthly average air pressure (hpa), monthly average temperature (°C), monthly average relative humidity (%), monthly average wind speed (m/s), monthly sunshine hours (h) and monthly sunshine percentage (%) in 17 cities of Hubei province, China, namely, Wuhan, Huanggang, Jinmen, Xiangyang, Xiaogan, Yichang, Shiyan, Jinmen, Enshi, Xianning, Huangshi, Suizhou, Ezhou, Tianmen, Xiantao, Qianjiang, Shennongjia, which are acquired from Hubei Provincial Meteorological Bureau. As for solar radiation, the authors have got the monthly observation data in 2014-2016 of Wuhan and Yichang from Hubei Provincial Meteorological Bureau. For the rest of all other cities, the authors calculated using the formula of Section 2.1. In the formula (1), the empirical coefficients a and b come from the results measured by the Regional Planning Office of Agricultural Climate of the Hubei Provincial Meteorological Bureau.

3. DISTRIBUTION OF SOLAR AND WIND ENERGY RESOURCES IN HUBEI

3.1 Temporal and Spatial Distribution of Solar Energy Resources

3.1.1 Spatial Distribution

In this paper, the authors have drawn the spatial distribution map for the solar radiation in Hubei province by using the mapping function of ArcGIS (see Figure 2). As can be seen from Figure 2, the total solar radiation in Hubei province is between 4055.87-5078.375078.37MJ/m^2, which is characterized by high in the Northeast and low in the southwest. More specifically, Shiyan, Suizhou, Xiaogan, Wuhan, Ezhou and Huanggang haves higher values of total radiation, for instance, Shiyan is the highest with an annual total radiation of 5078.37MJ/m^2; followed by Shengnongjia, Xiangyang, Jinmen, Tianmen, Qianjiang, Xiantao, Jinzhou, Xianning and Huangshi, with the annual average ranging from 4065.27 to 4672.32MJ/m^2; whereas, the lowest appears in Enshi and Yichang, with the annual average of about 4060MJ/m^2, and Yichang is the lowest, with only 4055.87MJ/m^2. Throughout Hubei province, the annual average sunshine hours are between 1275 and 2094h, with the provincial mean value of 1697h. The overall distribution trend is similar to that of solar radiation, i.e., high in Shiyan, Suizhou, Xiaogan, Wuhan, Ezhou and Huanggang and low in Enshi and Yichang (see Figure 3).

3.1.2 Seasonal Distribution

The estimation results of this study show that the time distribution of the total amount of radiation throughout Hubei is concentrated and the seasonal variation is great (see Table 1). The average monthly radiation in Hubei is between 174 and 235 MJ/m^2, with variances throughout the year. In winter (from December to February), the monthly radiation is the lowest (February is the least); After March, it increases significantly (in April, it ranges between 376 and 526MJ/m^2, almost twice as much ad February); Summer is the season of highest solar radiation throughout the year (in July, the value is between 551 and 647MJ/m^2); In autumn, after August, it begins to reduce significantly, and in November, it is about 191-298MJ/m^2, decreasing by 349-360MJ/m^2 as compared to July. From an overall perspective, the seasonal variances of Hubei's solar radiation feature a peak-valley pattern.

As for the seasons, summer is the highest, followed by spring and autumn, and winter is the lowest. Sunshine hours, as one of the important meteorological parameters to indicate the richness of solar energy resources, changes dramatically with seasons, with the monthly mean value in July being the highest and February the lowest. In general, the most sunshine hours appear in summer, followed by spring and autumn, and the least occur in winter. Comparing Table 1 and Figure 3, it can be seen that the distribution of sunshine hours in Hubei province is basically synchronized with that of the solar radiation.

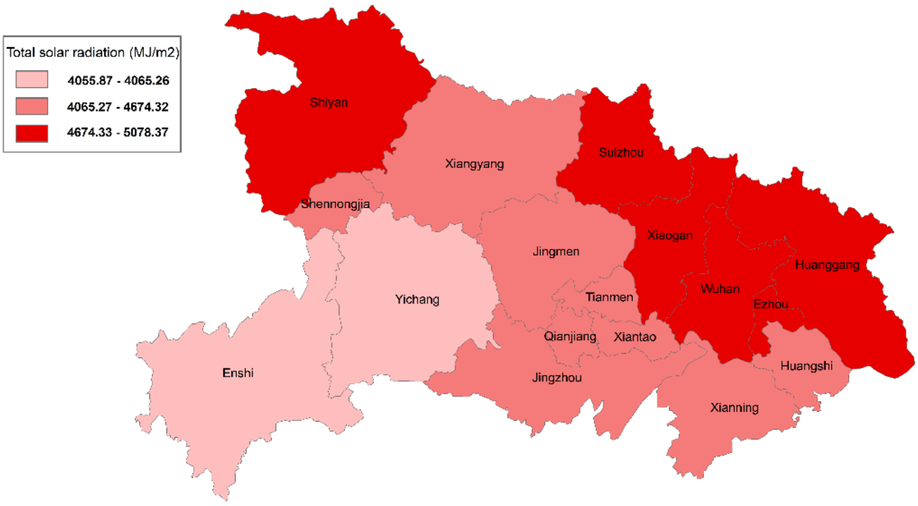

Fig. 2. Spatial distribution chart of yearly total solar radiation in Hubei province.

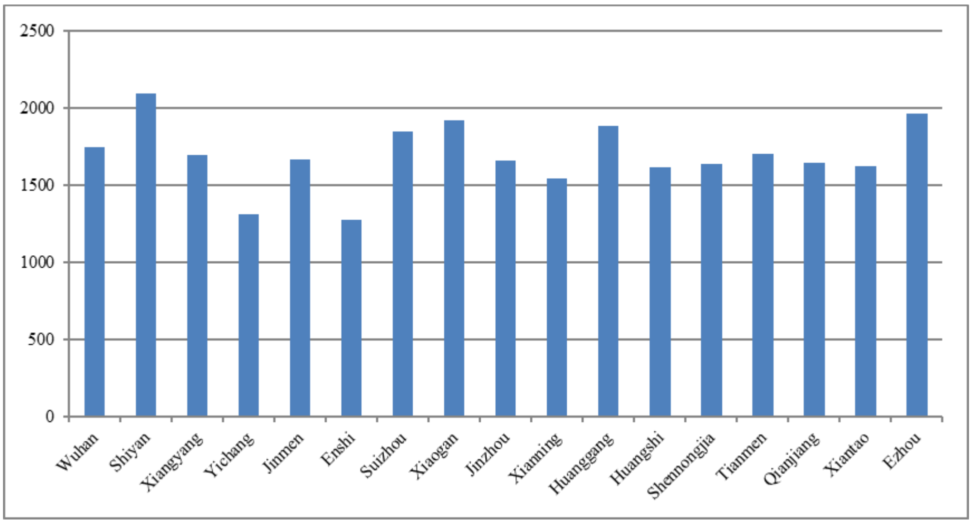

Fig. 3. Spatial variation of annual average sunshine hours in Hubei province.

Table 1. The total solar radiation in Hubei ($\times 10^{8}$J·m^{-2}).

Month	1	2	3	4	5	6	7	8	9	10	11	12	The average annual
Wuhan	2.42	2.12	3.66	4.26	4.61	4.77	6.17	5.48	4.13	3.76	2.68	2.68	46.74
Shiyan	2.69	2.35	4.37	5.26	5.34	5.75	6.3	5.45	4.18	3.79	2.66	2.67	50.78
Xiangyang	2.13	2.07	3.64	4.69	4.91	4.99	5.7	5.01	3.77	3.57	2.47	2.46	45.42
Yichang	2.09	1.83	3.29	3.83	3.99	4.02	5.51	4.86	3.51	3.23	2.23	2.16	40.56
Jinmen	2.39	2.17	3.76	4.19	4.47	4.98	5.99	5.28	3.79	3.58	2.46	2.41	45.47
Enshi	1.90	1.74	3.38	3.76	4.08	4.52	5.48	5.48	3.47	3.09	1.91	1.85	40.65
Suizhou	2.55	2.19	3.85	4.76	4.86	5.37	6.18	5.19	3.82	3.67	2.61	2.66	47.71
Xiaogan	2.60	2.25	3.80	4.33	4.86	5.04	6.47	5.71	4.21	3.97	2.76	2.88	48.94
Jinzhou	2.47	2.07	3.74	4.10	4.47	4.63	6.31	5.53	3.76	3.53	2.50	2.52	45.63
Xianning	2.42	2.03	3.45	4.07	4.33	4.46	5.89	4.80	3.79	3.73	2.58	2.48	44.05
Huanggang	2.45	2.16	3.77	4.46	4.72	5.22	6.22	5.80	4.28	4.00	2.83	2.76	48.68
Huangshi	2.23	2.00	3.63	4.27	4.65	4.81	5.76	4.97	3.85	3.83	2.66	2.49	45.14
Shennongjia	2.49	2.18	3.83	4.30	4.61	4.93	5.53	4.92	3.80	3.50	2.51	2.52	45.13
Tianmen	2.39	1.99	3.67	4.18	4.63	4.84	6.31	5.54	3.89	3.62	2.65	2.55	46.26
Qianjiang	2.35	1.97	3.52	4.06	4.49	4.86	6.36	5.42	3.74	3.65	2.55	2.53	45.47
Xiantao	2.35	2.06	3.56	4.26	4.38	4.70	6.31	5.40	3.94	3.64	2.63	2.51	45.73
Ezhou	2.63	2.29	3.88	4.65	4.95	5.29	6.38	5.55	4.41	4.02	2.98	2.89	49.90

Data source: Analyzed by the authors based on data from the Hubei Provincial Meteorological Bureau.

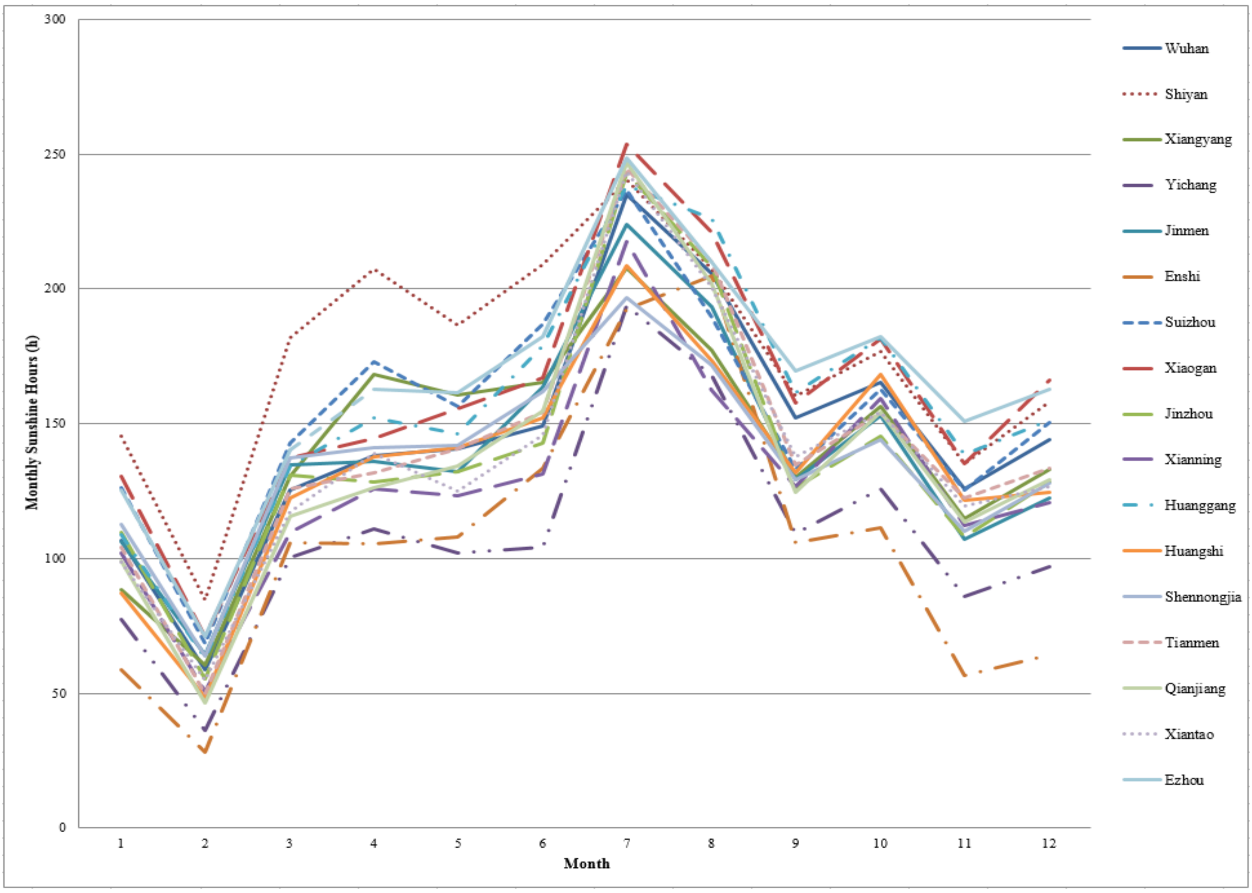

Fig. 4. The monthly variation of sunshine hours in Hubei province (h).

3.2 Temporal and Spatial Distribution of Wind Energy Resources

3.2.1 Spatial Distribution

In this paper, the authors have drawn the spatial distribution map of 10m for the annual mean wind speed in Hubei province by using the mapping function of ArcGIS (see Figure 6). Through comparison and analysis of Figure 5 and Figure 6, it was found that the spatial distribution characteristics of the annual mean wind speed and wind energy density in Hubei province are basically consistent with each other, and the overall distribution feature is: the wind energy resources in the middle-east are more abundant than the western part of Hubei. Specifically, the most abundant wind energy resources are concentrated in Xiangyang and Jinmen. In this area, the annual average wind speed is up to 3.6 m/s, and Jinmen's annual wind power density reaches 282.63 W/m^2, followed by Xiaogan, Huanggang, Wuhan, Xiantao, Xianning, Jinzhou and Tianmen, where the annual average wind speeds range between 1.79-2.06 m/s and annual wind power densities are around 40.48-52.61 W/m^2; whereas the least occurs in Shiyan, Suizhou, Enshi, Huangshi, Shennongjia, Qianjiang, Ezhou and Yichang, with the average wind density of 40 W/m^2 or slower.

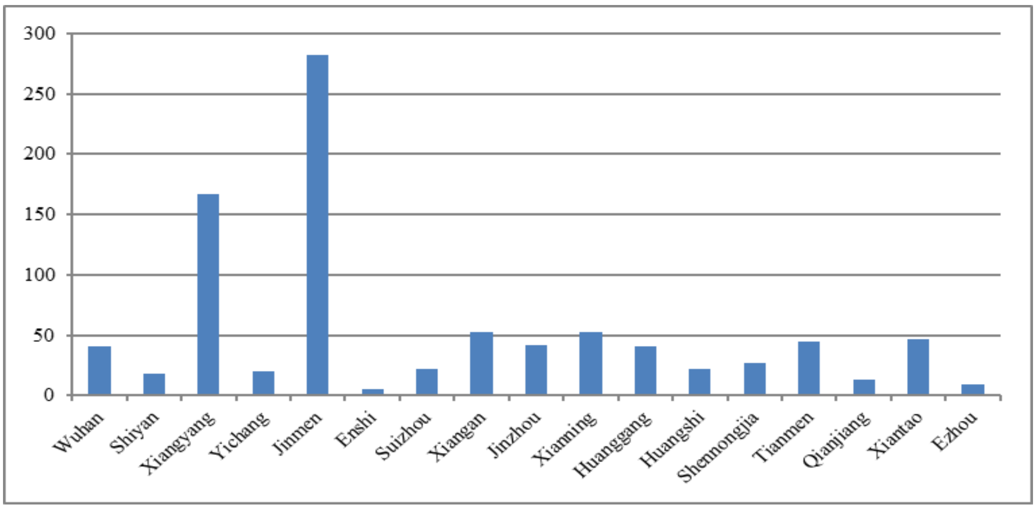

Fig. 5. Annual wind energy density in Hubei province (W/m^2).

Fig. 6. Distribution graph of annual mean wind speed in Hubei province.

3.2.2 Seasonal Distribution

As can be seen from Figure 7, the average wind speed distribution in Hubei province has obvious seasonal variations. In summer, July's average wind speed is the maximum, whose monthly average is up to 3.5 m/s in Xiangyang; After august, the wind speed begins to decrease, until October, the wind speed reaches the minimum with the monthly average of only 0.8 m/s in Enshi; when it enters winter, the wind speed in the province starts to gradually increase; in March of spring, the wind speed reaches another high value of the year. From Table 2, the monthly average wind energy distribution characteristics and the average wind speed in Hubei are basically the same; as for seasons, the overall performance is the highest in spring and summer, followed by winter with the lowest in autumn.

Table 2. Monthly wind energy density in Hubei (W/m^2).

Month	1	2	3	4	5	6	7	8	9	10	11	12	The average annual
Wuhan	32.76	69.43	58.38	51.22	27.19	27.14	70.82	69.01	20.64	11.97	18.65	28.62	40.48
Shiyan	10.67	15.68	22.57	26.28	24.79	17.02	19.39	18.20	11.21	11.54	13.95	19.62	17.58
Xiangyang	103.85	175.67	299.55	251.52	193.93	118.09	287.71	139.50	90.43	96.87	123.44	127.13	167.31
Yichang	20.04	19.76	28.89	20.42	19.07	17.81	25.23	20.34	15.57	14.27	12.54	23.20	19.76
Jinmen	295.75	427.72	395.02	264.10	221.57	172.67	170.08	332.93	274.19	215.65	316.72	305.17	282.63
Enshi	4.46	3.93	5.27	6.54	4.99	6.25	9.76	9.05	4.59	2.91	2.74	2.75	5.27
Suizhou	21.78	33.22	33.32	27.15	16.49	12.42	36.83	29.27	12.86	12.64	15.66	17.80	22.45
Xiaogan	47.69	86.67	65.99	54.08	48.62	37.81	53.99	72.43	40.17	29.18	42.86	45.48	52.08
Jinzhou	26.28	56.44	47.65	41.20	35.09	32.60	80.06	62.90	39.59	17.04	24.71	35.84	41.62
Xianning	54.56	42.26	60.48	63.46	47.03	40.31	80.88	57.92	36.73	46.20	49.15	52.30	52.61
Huanggang	40.69	52.47	60.11	56.76	39.44	35.16	36.46	39.19	23.47	24.93	33.05	47.97	40.81
Huangshi	12.84	22.65	26.74	28.58	23.74	23.01	26.15	24.45	17.86	14.95	16.56	20.55	21.51
Shengnongjia	37.12	34.74	44.34	31.47	22.64	18.16	18.14	16.08	13.39	17.50	30.98	35.02	26.63
Tianmen	32.62	63.16	64.95	44.23	34.21	29.31	97.62	57.39	24.58	20.73	26.19	40.08	44.59
Qianjiang	10.93	18.49	19.62	12.87	8.97	6.33	30.40	17.38	8.34	5.91	9.06	12.69	13.42
Xiantao	34.87	73.54	68.89	50.70	36.66	27.79	72.22	64.23	33.56	27.83	31.72	37.13	46.60
Ezhou	7.03	9.02	8.98	11.95	10.63	8.69	12.35	12.42	6.84	5.90	6.90	8.14	9.07

Data source: Analyzed by the authors based on data from the Hubei Provincial Meteorological Bureau.

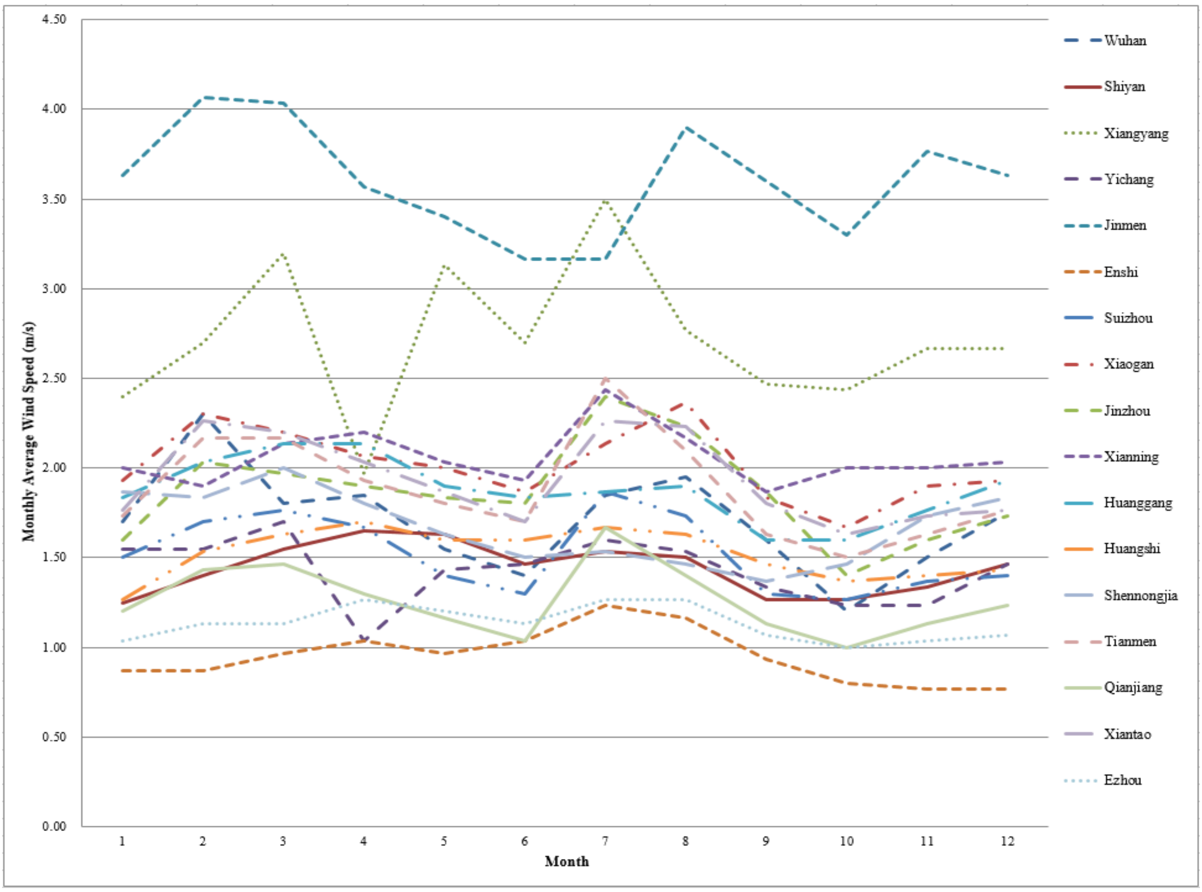

Fig. 7. Monthly variation of mean wind velocity in Hubei (m/s).

Table 3. Solar energy zoning indicator of Hubei province.

Partition	Annual total solar radiation(MJ/m^2)	Annual total sunshine hours(h)
First solar energy resources available area	>4600	1710-2100
Second solar energy resources available area	4200-4600	1500-1710
Solar resource poor area	<4200	<1500

4. COMPLEMENTARITY OF SOLAR AND WIND ENERGIES IN HUBEI

4.1 Spatial Complementarity

From the above analysis, the authors understand that there is an obvious complementarity between solar and wind energy resources in specific areas of Hubei province. In this paper, the authors present the complementary relationship between solar and wind energy resources by zoning the province with ArcGIS. Besides, the authors have built and measured the solar and wind energy complementary index, quantitatively analyzing the complementarity of solar and wind energy resources in the province.

4.1.1 Solar Energy Resource Zoning

Based on the total solar radiation, Wang *et al.* [65] divided the solar energy resources in China into 4 levels, rich areas, relatively rich areas, relatively poor areas and poor areas. In order to better develop and utilize solar energy resources in Hubei province, solar energy zoning standards for the province for mapping the solar energy zones need to be developed. In this paper, based on the national division of solar energy resources, the authors divided the annual total solar radiations and introduced the sunshine hours as another reference indicator (see Table 3).

According to district standards in Table 3, the authors considered the two indicators comprehensively, and each indicator is equally important. The area belongs to the zone when its two indicators satisfy the zone's standards at the same time. Meanwhile, ArcGIS was used to map the regional distributions of solar energy as shown in Figure 8.

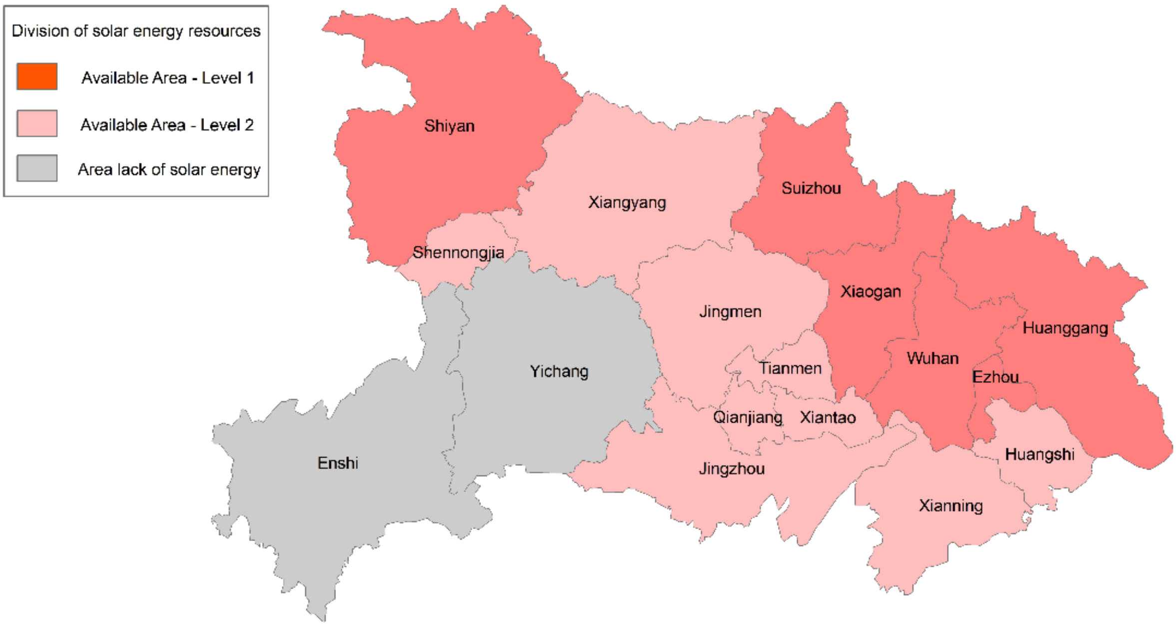

Fig. 8. Zoning map of solar energy resources in Hubei province.

Table 4. Indicator of wind energy zoning in Hubei province.

Wind energy zoning	10m high wind energy density($W \cdot m^{-2}$)
Rich area	>150
Relatively rich area	100-150
Available area	50-100
Poor area	<50

Fig. 9. Zoning of wind energy resources in Hubei province.

4.1.2 Wind Energy Resource Zoning

The volume of wind energy in a given unit area at a given time period is an effective indicator to characterize the richness of wind energy resources, referring to the district standards of "The Technical Requirements for Wind Resource Assessment" [66], based on the actual data of this study, the authors made the average wind energy as wind energy zoning indicator of Hubei province (see Table 4).

According to the above zoning standards, the ArcGIS software to map the regional distribution of wind energy in Hubei province (see Figure 9) was adopted.

Table 5. Annual average solar energy and wind energy resource reserves in Hubei province (kWh/㎡).

Area Code	Annual average wind energy reserves	Annual average solar energy reserves	Total reserves of average annual solar and wind energy	Difference reserves of average annual solar and wind energy	Complementary index
Enshi	46.17	1129.24	1175.41	1083.07	0.92
Ezhou	79.46	1386.19	1465.65	1306.73	0.89
Qianjiang	117.53	1263.19	1380.72	1145.66	0.83
Shiyan	153.98	1410.66	1564.64	1256.68	0.80
Suizhou	196.68	1325.39	1522.07	1128.70	0.74
Huangshi	188.39	1254.02	1442.41	1065.63	0.74
Yichang	173.10	1126.63	1299.73	953.53	0.73
Shennongjia	233.29	1253.61	1486.90	1020.32	0.69
Huanggang	357.48	1352.17	1709.65	994.69	0.58
Wuhan	354.64	1298.42	1653.06	943.78	0.57
Jinzhou	364.56	1267.50	1632.05	902.94	0.55
Tianmen	390.59	1284.96	1675.55	894.37	0.53
Xiantao	408.18	1270.29	1678.46	862.11	0.51
Xiaogan	456.23	1359.55	1815.78	903.32	0.50
Xianning	460.84	1223.60	1684.44	762.76	0.45
Jinmen	2475.84	1263.02	3738.86	1212.82	0.32
Xiangyang	1465.60	1261.64	2727.24	203.96	0.07

Data source: Analyzed by the authors based on data from the Hubei Provincial Meteorological Bureau.

4.1.3 Spatial Complementarity Measurement of Solar and Wind Energies

As can be seen from Table 5, except for a few areas (Jinmen, Xiangyang), the solar energy resources of most areas in Hubei are far more than the wind energy resource reserves.

From the above results, it can be easily found that: the solar and wind energies of Enshi, Ezhou, Qianjiang, Shiyan are highly complementary, especially in Enshi, its complementary index is up 0.92; Suizhou, Huangshi, Yichang, Shennongjia, Huanggang, Wuhan, Jinzhou, Tianmen, Xiantao, Xiaogan are moderate complementarity, whose complementary index ranges from 0.8 to 0.5. Among them, the solar energy resources of Suizhou, Huanggang and Wuhan are available, but their wind energy is poor; Jinmen and Xianning belong to the category of low complementarity; Xiangyang can be classified as no complementarity, whose complementary index is only 0.07, since its wind and solar energy reserves are almost equal.

4.2 Seasonal Complementarity

Through the analysis and study on the solar and wind energy monthly reserves of 17 cities in Hubei province, it is found that: except for some areas such as Jinmen, Huanggang, Shenlongjia and Xiaogan (they are complementary in the time dimension), the seasonal complementarity is very weak. Therefore, Jinmen, Huanggang, Shenlongjia and Xiaogan were taken as an example to analyze the seasonal complementarity of solar and wind energies for this province. As can be seen from Figure 10, the monthly solar energy reserves of Jinmen, Huanggang, Xiaogan, Shenlongjia are between 50 and 200 kwh/m^2, which are greater than those of the wind energy from a monthly perspective. Analyzing from the solar energy reserve distribution curve, it is found that that the solar seasonal variation in Hubei province is very obvious, with the most abundant solar energy resources appearing in summer especially in July, followed by spring and autumn, and the least occurs in winter. Contrary to the solar energy resource distribution trend, however, the wind energy reserves is more in spring and winter, with the most occurring in February, and the least comes in summer.

5. CONCLUSIONS AND PROSPECTS

5.1 Conclusions

From the above analyses, the following conclusions are drawn:

(1) The spatial distribution of the solar energy resources in Hubei features high in the northeast and low in the southwest, with distinct divisions of the four seasons. The total annual solar radiation across the province is between 4055.87 and 5078.37 MJ/m^2, with the most solar radiation appears in summer, followed by spring and autumn, and the least being in winter. Shiyan, Suizhou, Xiaogan, Wuhan, Ezhou and Huanggang is the area of high annual radiations, where the highest appears in Shiyan, which is the first class solar rich area; followed by Shengnongjia, Xiangyang, Jinmen, Tianmen, Qianjiang, Xiantao, Jinzhou, Xianning and Huangshi; whereas Enshi and Yichang is a solar energy deficient area.

(2) The wind energy resources in Hubei has the characteristic of high in the middle eastern region and low in the west, with the seasonal trend of strong in spring and summer, mild in winter, and weak in autumn. The overall distribution of wind energy resources in Hubei is: the wind energy resources are more abundant in the east-central part than those of the western part of Hubei; where the maximum wind speed appears in Xiangyang and Jinmen, with the

annual average wind speed of 3.6 m/s, and it is the wind resource rich area in Hubei province; followed by Xiaogan, Huanggang, Wuhan, Xiantao, Xianning, Jinzhou and Tianmen, with the least being Shiyan, Suizhou, Enshi, Huangshi, Shennongjia, Qiangjiang, Ezhou and Yichang, which is a wind resource deficient area. The wind energy density has obvious seasonal variations in different parts of Hubei, and it is most abundant in spring and summer especially in July, followed by winter, and the autumn being the least.

(3) The solar and wind energy resources in Hubei are complementary highly in space and slightly in season. From the aspect of space, Enshi, Ezhou, Qianjiang and Shiyan are the most highly complementary, with the complementarity indexes being 0.92,0.89,0.83,0.80; Huangshi and Suizhou are moderately complementary; Xianning and Jinmen are low complementary; Xiangyang's complementarity is extremely weak, with its complementary index of only 0.07. From the perspective of seasons, except Jingmen, Huanggang, Shennongjia and Xiaogan where the solar and wind in summer and winter has obvious complementarity, there is no complementarity between the two energy resources in all other parts of Hubei in terms of seasons.

5.2 *Policy Recommendations*

Based on the above conclusions, the following recommendations are proposed:

(1) Strengthening the development and utilization of solar energy in high solar radiation areas, such as Shiyan and Suizhou. In these areas, measures should be taken such as solar cookers and solar water heaters should be widely used in the rural areas. Solar energy can also be used for ice making and refrigeration. When solar radiation is weak in winter, solar energy can be combined with biomass energy (such as biogas) for the comprehensive utilization of these renewables.

(2) Considering the development of wind energy complementary with hydropower, so as to improve the energy structure and alleviate the power shortage in Hubei. In China's Hubei province, the terrain is very complex with mountainous areas (high, middle, low mountain) intricated with hills, uplands and plains. The wind is the largest meteorological element affected by terrain and geomorphology. Different terrain will lead to diversified wind speeds, e.g., the annual average wind speed is up to 3.6m/s in Jingmen, while the average annual wind speed is only 0.95 m/s in Enshi. Therefore, a tower with different heights should be built to carry out the encrypted observation according to the different terrains, providing a reference for the evaluation and development of macro wind energy resources and the micro siting of wind farms in Hubei province.

(3) In the regions with highly complementary solar and wind energy, targeted incentives and subsidy policies should be formulated to guide the effective use of the two complementary relationship and actively develop solar and wind energy resources, in an effort to improve the proportion of clean energy, including solar and wind powers, and reduce carbon dioxide emissions for the contribution to realizing green development.

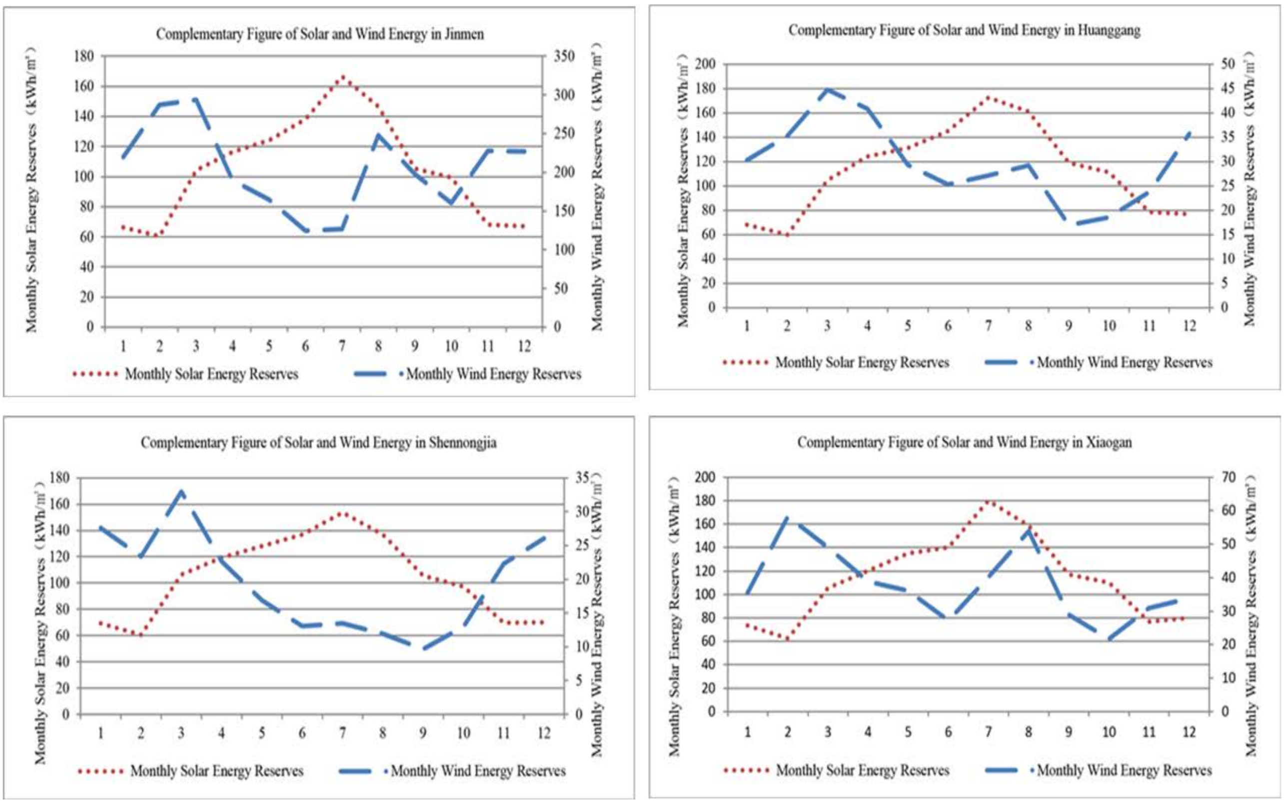

Fig. 10. Complementary diagram of solar energy and wind energy in Hubei.

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