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Review

Review of Research on the Present Situation of Development and Resource Potential of Wind and Solar Energy in China

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Abstract: To address the global warming issue, China is prioritizing the development of clean energy sources such as wind and solar power under its "dual carbon target". However, the expansion of these resources is constrained by their intermittency and the spatial and temporal distribution of wind and solar energy. This paper systematically reviews the evolution of wind and solar energy reserves, their development potential, and their current status in China from a geographical perspective. In conjunction with existing research, this paper anticipates future exploration in the realm of wind–solar complementary development or multi-energy complementary development, viewed through the lens of resource quantity. The anticipated findings are intended to furnish a theoretical foundation for further studies on the development and utilization of wind and solar energy resources within China.

Keywords: China; wind energy resources; solar energy resources; resource potential; research advances

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Citation: Li, T.; Liu, Y.; Lv, A. Review of Research on the Present Situation of Development and Resource Potential of Wind and Solar Energy in China. *Energies* **2024**, *17*, 4158. https://doi.org/10.3390/en17164158

Academic Editor: Francesco Nocera

Received: 21 July 2024
Revised: 19 August 2024
Accepted: 19 August 2024
Published: 21 August 2024

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), global warming is projected to exceed 1.5 °C within this century if carbon dioxide and other greenhouse gas emissions are not significantly reduced in the coming decades [1–3]. Over recent decades, China's rapid urbanization and industrialization have led to a continuous increase in total CO_2 emissions [4]. The International Energy Agency (IEA) data indicates that in 2007, China surpassed the United States as the world's largest CO_2 emitter, a trend that is expected to persist for an extended period [5]. In response to this situation, China has introduced the "double carbon target" development policy. This policy emphasizes the optimization of energy structures, the promotion of green energy sources such as wind, water, and solar power, and the reduction of fossil fuel usage [6].

China, characterized by its expansive territory, significant elevation differences, and intricate terrain, exhibits substantial variations in the potential for wind and solar energy resources. As of 2018, China's cumulative installed capacity for wind power and photovoltaic energy ranked first globally [7]. Notably, compared to the global growth rate of wind and solar resources, China's new energy growth rate is markedly faster. Furthermore, the development and utilization of these resources differs markedly across various regions [8,9]. Post-2010, the large-scale exploitation of wind and solar energy in China led to a disconnect between resource potential and actual development, resulting in low efficiency [10–13]. As of 2023, the waste rates for wind and solar energy in China stand at 3.1% and 2%, respectively. Notably, Qinghai Province has a waste rate exceeding 10% [14]. In the context of global warming, in order to achieve the strategic goal of carbon peak by 2030 and carbon neutrality by 2060, it is necessary for China to strengthen the development of clean resources such as wind energy and solar energy, improve the development efficiency of resources, and reduce greenhouse gas emissions generated by fossil energy.

However, in contrast to traditional thermal power generation, hydroelectric, and nuclear power generation, wind and solar power generation exhibit characteristics of intermittence and volatility. These traits result in a mismatch between the cost and profit return levels associated with resource development and utilization [15–17]. With the large-scale integration of wind and solar into the power system, the intermittency and volatility characteristics of wind and solar resources are gradually amplified. In practice, developers often find themselves investing more funds but achieving lower profit returns, which can diminish their confidence in the development and utilization of climate resources [18,19]. Particularly for developing countries and regions, their low economic status and limited scientific and technological development capacity may cause them to use fossil energy profits that exceed those from green energy within a short period [7,15]. Therefore, for resource developers, there is an urgent need to address the continued low profitability of wind and solar resources due to inconsistent resource output over time.

To sum up, this paper initially examines the evolution and developmental potential of China's wind and solar energy resources from a geographical standpoint. It then provides a comprehensive summary of the current development stage of these resources, evaluating their respective advantages and disadvantages. The paper concludes by outlining the methods of development and utilization, the driving process, and future assurance measures for wind and solar energy resources in China. This is intended to serve as a reference for future development and utilization evaluations of these resources within the country.

2. Resource Potential Characteristics of Wind and Solar Energy Resources in China

Wind and solar energy are inherently unstable climate resources. Their availability is significantly influenced by weather, climate, topography, and human activities, resulting in pronounced diurnal, seasonal, and interannual variations [20–22]. China's geographical position situates it in the eastern part of Eurasia, bordering the Pacific Ocean to the east, and the land region experiences more rapid heat gain and loss than the ocean. This is particularly evident in both seasonal and non-seasonal regions, due to the significantly larger specific heat capacity of the ocean compared to the land [23,24].

China boasts a substantial amount of wind and solar energy resources, with these resources exhibiting distinct regional characteristics [7]. In terms of spatial distribution, regions with an effective wind energy density exceeding 100 W/m^2 are primarily located in the northern part of Inner Mongolia, the eastern region of Jilin Province, Heilongjiang Province, and the Liaodong Peninsula (Figure 1a,b). Generally, the effective wind energy density falls within the range of 50–100 W/m^2, encompassing 53.39% of the country's total land area (Figure 1e). Conversely, the total annual solar radiation in China's non-monsoon region significantly surpasses that of the monsoon region (Figure 1c,d). Spatially, the total solar radiation is predominantly found on the order of 5040–6300 MJ/m^2, representing 44% of China's total land area (Figure 1f).

Meanwhile, China's wind and solar energy resources are predominantly located in the plains and plateaus, far from its core urban areas. This geographical distribution offers favorable conditions for their development and utilization [25,26]. However, from a resource development standpoint, the harsh natural environmental conditions in Northwest China and Qinghai–Tibet, coupled with frequent regional climate change and extensive power transmission lines pose significant challenges for the effective development and utilization of these resources. In conclusion, while China's wind and solar energy resources theoretically possess substantial development potential, their actual utilization may be limited. A comprehensive and rational assessment is therefore necessary.

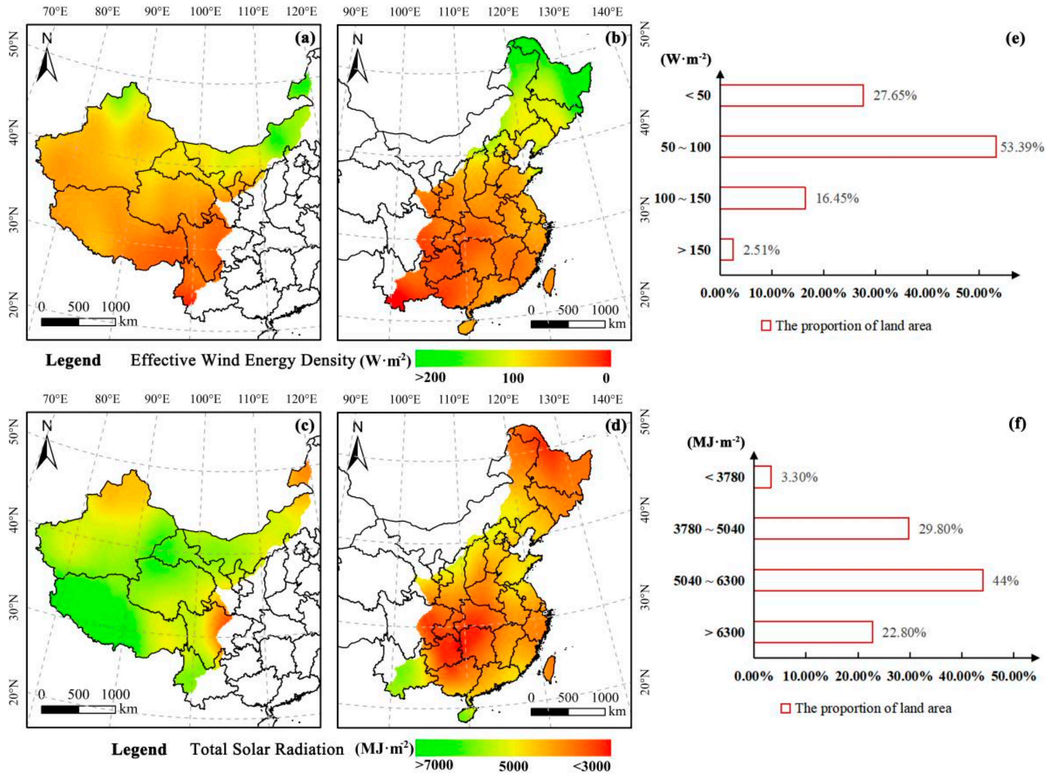

Figure 1. Spatial distribution of annual average effective wind energy density (**a**,**b**) and total solar radiation (**c**,**d**) in China. (Note: (**a**,**c**) represent the monsoon regions; (**b**,**d**) represent the non-monsoon regions; (**e**) represents area ratio of annual average effective wind energy density; (**f**) represent area ratio of annual total solar radiation. Data from the China Energy Administration, the China Yearbook (2010–2020), and Lv et al., 2022 [7]).

In addition, according to the provisions of "Wind farm wind energy Resource Evaluation Method" (GB/T 18710-2002 [27]) and "Solar energy resource evaluation method" (GB/T 37526-2019 [28]), there are obvious differences between the evaluation indicators of wind energy resources and solar energy resources. The commonly used evaluation indices of wind energy resources include average wind speed, wind direction frequency, wind power density, effective hours, turbulence intensity of measuring station, wind energy resource reserves, technical exploitable amount of wind energy resources, etc. [20–22]. However, depending on the mode of propagation, solar energy is divided into total radiation, direct radiation, and scattered radiation. Based on the amount of solar radiation at different time scales, indices such as richness, stability, and direct exposure ratio are usually used to evaluate solar energy resources [23,24].

3. Development and Utilization of Wind and Solar Energy Resources in China

In addition to water energy resources, solar and wind energy resources are the main green energy resources, and the evaluation of their resource reserves are an important basis for future development and utilization. At present, the research methods for wind and solar energy resources can be summarized as follows: the evaluation method based on observation, the evaluation method based on numerical models, the evaluation method based on satellite remote sensing, and the evaluation method based on re-analysis data [29–32]. Since the advantages and disadvantages of different methods are significantly different (Table 1), more basic data will be needed to correct the evaluation model in the future.

Table 1. Major research methods for wind and solar energy resources [29–32].

Method	Advantages	Disadvantages
The evaluation method based on observation	Based on the measured data; the data quality is better, and the error in calculation is relatively low.	The number of sites is limited and unevenly distributed, and the research cost is relatively high.
The evaluation method based on numerical models	It can evaluate resources in areas without measured data, which is suitable for future prediction.	There are large uncertainties in the data.
The evaluation method based on satellite remote sensing	The coverage area in the spatial scale is relatively extensive, and it provides top-down observation data with high spatiotemporal resolution, with spatiotemporal continuity.	The treatment of clouds and aerosols is not perfect. The data time scale is relatively short and cannot provide real-time data.
The evaluation method based on re-analysis data	Relatively comprehensive factors can be considered, and its advantages are as follows: multiple data sets and easy access; low research costs; relatively long time scales; and relatively wide spatial distribution.	Data quality cannot be guaranteed, and local applicability needs to be assessed.

3.1. Development and Utilization of Wind Energy Resources in China

Among the myriad of renewable resources, wind energy has progressively emerged as a pivotal element in the contemporary energy landscape, attributed to its abundant reserves, renewability, widespread distribution, and environmentally benign attributes (Figure 2) [6,7]. Since 1970, numerous scholars have contributed significantly to the evaluation of wind energy reserves and their spatiotemporal evolution, development, and utilization [33–36]. Concurrently, advancements in remote sensing technology and numerical simulation methods have facilitated Chinese researchers' progress in assessing wind energy resources, particularly in marine or intricate geomorphic regions where meteorological observation data are scant [37–39].

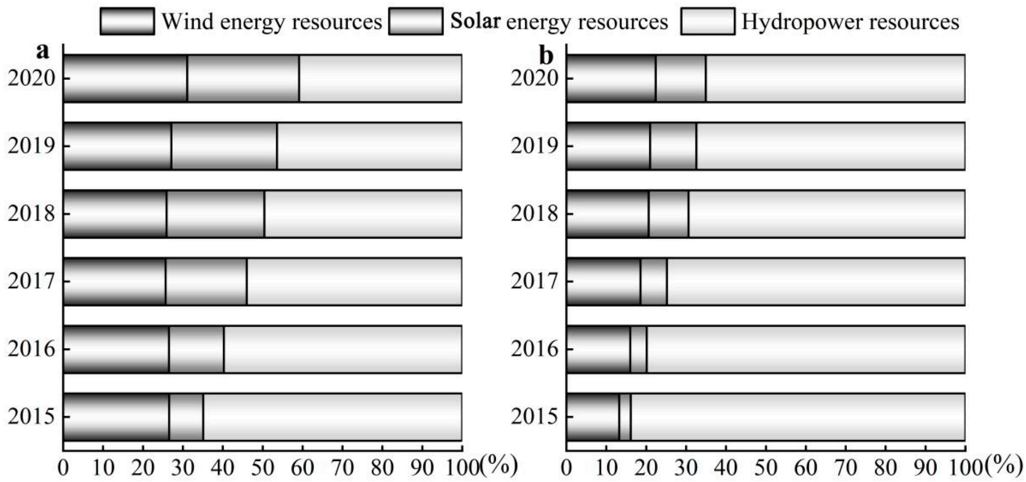

Figure 2. The proportion of installed capacity (**a**) and power generation (**b**) of renewable energy in China from 2015 to 2020. (Note: (**a**) represents the percentage of installed capacity by three renewable sources. (**b**) represents the percentage of electricity generated by three renewable sources. Data from the China Energy Administration and the China Yearbook (2015–2020).).

Since 2000, China has embarked on an aggressive development of wind power. As the technology has matured and evolved, there has been a significant increase in the installed capacity of wind power in China from 2015 onwards [40,41]. According to data provided by the IEA [40,41], as of 2022, China's cumulative installed capacity of wind power reached 3.65×10^4 million kW. This represents 14.3% of the country's total installed power generation capacity. Of this, the onshore wind power installed capacity of 3.046 × 10^3 million kW has held the world's top position for 13 consecutive years. The offshore wind power installed capacity of 3.35 × 10^4 million kW also ranks first globally. In 2021, when China's cumulative installed capacity of wind power exceeded 3 × 10^4 million kW, it accounted for 40.40% of the world's total installed capacity of wind power (8.37 × 10^4 million kW). However, by the end of 2022, wind power only contributed a total of 8.8% to China's electricity generation. This is significantly lower than the 14.3% contribution from the installed wind power capacity, indicating that the efficiency of wind power development and utilization lags behind traditional thermal and hydropower sources [7–9].

In addition, by the conclusion of 2021, China's abandoned wind power had reached 2.06 × 10^6 million kW·h. This number represents a significant improvement in the development efficiency of China's wind power, particularly when compared to the 4.5 × 10^6 million kW·h of China's abandoned wind power from 2016–2017. Despite the gradual increase in the installed scale of wind power, the amount of abandoned hydropower and wind power remains almost identical. This suggests that the development efficiency of hydropower significantly surpasses that of wind power [42,43]. From the perspective of provincial administrative regions (Figure 3), China's abandoned wind power in 2020 is mainly concentrated in northern China. Consequently, the volatility and intermittency of wind energy resources are crucial for ensuring the safe operation and efficient utilization of large-scale wind power.

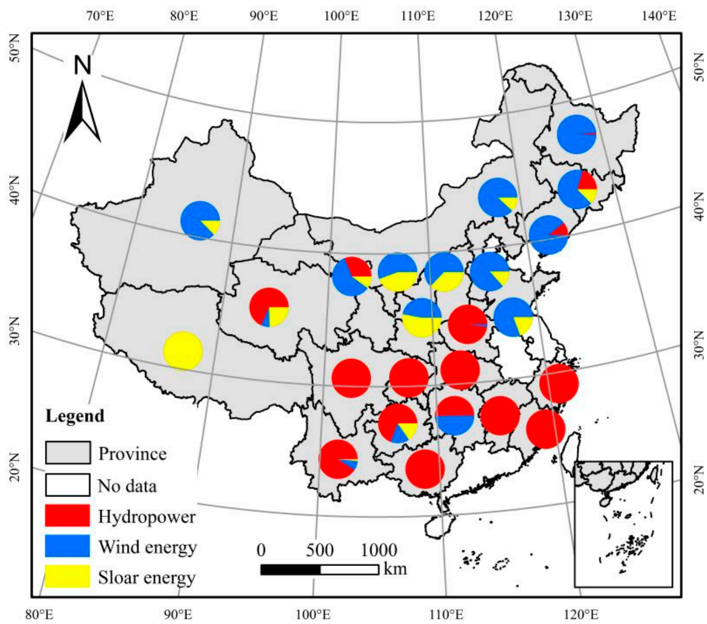

Figure 3. Spatial distribution of the proportion of abandoned wind, solar and hydropower by province in China in 2020. (Note: Data from the China Energy Administration and the China Yearbook [44–46]).

3.2. Development and Utilization of Solar Energy Resources in China

The average solar radiation intensity in Earth's orbit (AMO) is approximately 1.37 × 10^3 W/m^2 [40]. Despite the sun's total radiation energy being 2.2 billion times greater, its energy intensity on Earth reaches 1.73 × 10^5 Tw (where 1 TW equals 10^9 kW) [47,48]. Although the total amount of solar radiation that reaches the Earth's surface is substantial, the relatively low energy flux density necessitates the use of a larger area of energy conversion equipment for solar energy development and utilization. Furthermore, factors such as diurnal effects, underlying surface topography, latitude seasonality, and altitude significantly limit the efficiency of solar energy resource development and utilization, thereby increasing the associated costs [49–52].

Since 1960, numerous scholars have made significant contributions to the study of spatiotemporal evolution, regionalization characteristics analysis, and the development and utilization of solar energy resources in China [47–49]. The Chinese government's sustained investment in new energy has led to a rapid expansion of photovoltaic power generation since 2015 (Figure 2). According to data released by the IEA [44,45] and the China Energy Administration, at the end of 2022, the average utilization hours of solar power generation in China reached 1202 h, an increase of 39 h. The annual solar power generation is expected to be 4.251×10^3 million kW·h, marking an increase of approximately 30.4% over 2021. Solar energy accounts for 4.9% of the country's total annual power generation and 13.5% of the total annual power generation from non-fossil sources [44,45]. Furthermore, according to data released by the IEA [44,45], at the end of 2022, China's installed solar power capacity reached 3.926 million kW, representing 15.3% of China's cumulative installed capacity and 44% of the global installed solar power capacity.

In comparison to wind and hydropower, solar power generation is relatively less efficient [46,53–55]. As of the end of 2021, China's abandoned solar power had a surplus of 6.78 billion kW·h. The photovoltaic power generation utilization rate was approximately 97.8%, marking an increase of about 0.8% [19]. This contrasts with the 7 billion kW·h of China's abandoned solar power in 2016–2017. However, with the gradual expansion of the installed scale of solar power generation, the development efficiency of China's optoelectronics has significantly improved [44–55]. From the perspective of provincial administrative regions (Figure 3), the regional proportion of abandoned solar power in China in 2020 is significantly lower than the regional proportion of abandoned wind power and abandoned hydropower.

4. Driving Factors for the Development and Utilization of Wind and Solar Energy Resources in China

4.1. Direct Impact of Regional Policies and Management Measures

Government policies and regulatory measures have been instrumental in the evolution of the wind and solar industry. Qiu et al. [56], based on their research into the concentrated development of renewable energy in China's Tibetan Plateau region, posit that policy support is vital for enhancing the efficiency of wind and solar resource development. The Chinese government could foster wind and solar projects in this region by implementing subsidies, tax incentives, and feed-in tariffs. Alternatively, governments could encourage both private and public investment in wind and solar projects by establishing reasonable market access mechanisms [57,58].

Concurrently, the National Energy Administration of China, along with other regulatory bodies, has ensured the logical arrangement and sustainable progression of wind and solar projects through meticulous planning and oversight [59]. Drawing from research on the combined development of offshore wind and wave energy, Wen et al. introduce an exponential methodology that incorporates policy and market mechanisms to assess the viability of wind and wave projects [57]. Compared with other regions, a sound top-down system enables the government to achieve a higher level of policy driving. For example, although Africa and the Middle East have rich resource reserves, they lack a stable production environment, so that their policy-driven effects are not obvious. In conclusion, this suggests that the evolving Chinese electricity market mechanism and carbon trading system can offer more substantial economic value and environmental advantages for the advancement of wind and solar energy resources [60,61].

4.2. The Promoting Role of Science and Technology and Development Mode

Technological advancements are the primary drivers of wind and solar energy resource development. Currently, these resources are typically developed and utilized using a singular resource approach, such as regional hydropower stations, photovoltaic power stations, and wind farms [62,63]. However, this single resource development model is not optimal for maximizing resource potential, leading to inefficiencies and wastage within the region [64]. To address this issue, some scholars have proposed a joint and complementary development approach that utilizes two (wind–solar) or multiple resources (water–wind–solar), aiming to mitigate the waste caused by the temporal fluctuations and intermittency of climate resources. This approach seeks to enhance the efficiency of resource development and utilization [65–67]. For instance, the lower basin of China's Jinsha River serves as a prime example of this joint and complementary development model for scenic water resources [7,68]. Consequently, there is an urgent need to explore alternative technical methods for resource development, such as improving power storage technology. In regions unsuitable for multi-resource joint and complementary development, electric energy storage can be employed to boost the efficiency of resource development and utilization.

Numerous scholars and governments have proposed and implemented various energy storage methods, including mechanical, electromagnetic, phase change, and electrochemical energy storage [69]. However, for large-scale regional resource development, the energy storage capacity of a single facility is often limited. Factors such as profit cost, energy storage efficiency, and energy conversion must be taken into account [70,71]. In the application of energy storage technology, a pumped storage power station is the most effective way to promote the large-scale application of new energy, realize the complementarity of multiple energy sources, and build a safe, reliable, and economically flexible power system. According to current research, pumped storage power stations represent the most mature energy storage method, boasting the highest technical level and economic benefits [72,73]. Nevertheless, the choice of energy storage method and scale in different regions is largely determined by the regional economic level, total consumption, and profit returnability [73]. For instance, China's pumped storage power stations are predominantly located in its eastern coastal areas (Figure 4), with relatively few in areas possessing high development potential and climate resources. This distribution pattern is due to China's economic industries and population being primarily concentrated in the eastern coastal areas, which results in high regional energy and power consumption. This creates favorable conditions for the large-scale construction of pumped storage power stations in the eastern region [74,75].

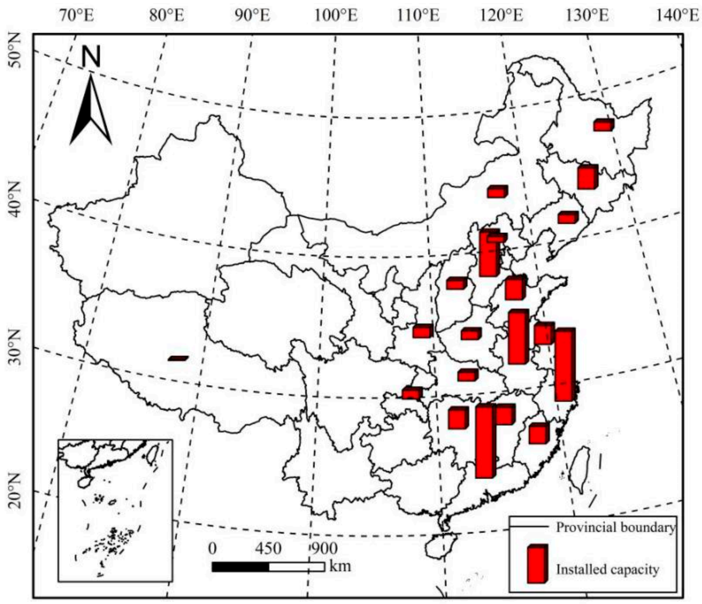

Figure 4. Spatial distribution of China's installed capacity of pumped storage power stations in 2020. (Note: Data from the China Energy Administration and the China Yearbook).

However, there is a real problem in that technological progress depends on the economic level of countries and regions. In areas with low economic development, short-term profit returns may be considered more. The development and utilization of wind and solar energy resources cannot be profitable in the short term, which hinders the development and utilization of wind and solar energy and other resources. Meanwhile, this is quite different from the problems faced by China, the United States, and other economically advanced regions in the development of wind and solar resources.

4.3. Indirect Effects of Climate Warming and Air Pollution

According to the European Copernicus Climate Change Service, the world has surpassed its hottest monthly record for 12 consecutive months since June 2023. During this period, the global average temperature has risen by 1.64 °C compared to the pre-industrial Revolution era. Fossil fuel power generation, which is the primary method of electricity production, contributes to various atmospheric pollutants, including SO_2, NO_X, and CO_2 [76,77]. Among these, carbon dioxide emissions pose the most significant greenhouse gas problem and are the principal cause of global warming. The reduction of carbon emissions to prevent further increases in Earth's temperature has garnered considerable attention in numerous countries [61]. Over recent decades, this issue has become a focal point of academic and public discourse. Consequently, the adoption of clean renewable energy as an effective alternative to fossil fuels is crucial for reducing global carbon emissions and mitigating pollution resulting from electricity production, thereby protecting the atmosphere and global climate [77,78].

In 2015, the United Nations Climate Change Convention, held in Paris, saw the unanimous agreement of 195 countries to limit global warming to less than 2 °C. The majority of these nations pledged to enhance the development and utilization of renewable energy and to ensure a proportionate share of energy efficiency through independent national optimization of their energy structures [79]. Approximately 70% of the world's nations have expressed their commitment to developing renewable energy as a means of mitigating global warming. Concurrently, several countries have committed to reforming their budgetary allocations for fossil fuel extraction [80]. These collective efforts significantly contribute to the expectation that an increasing number of countries will transition from using fossil fuels to generating electricity through renewable energy sources in the future. However, as mentioned above, this can lead to national or regional economic pressures that hinder the development of wind and solar resources.

In this context, China has introduced the "double carbon target" policy. This energy policy is designed to vigorously develop green energy sources such as wind, water, and solar power in an effort to reduce fossil fuel usage [6]. Data indicates that from 2010 to 2020, China's wind power generation capacity increased from 2.958×10^3 MW to 2.817×10^4 MW, hydropower generation capacity rose from 2.161×10^4 MV to 3.703×10^4 MV; and solar power generation capacity expanded from 26 MW to 2.536×10^4 MW. Furthermore, China's carbon emission intensity in 2020 was expected to be 48.4% lower than it was in 2005 [7,81]. Despite China remaining the world's largest CO_2 emitter, the Chinese government's promotion of green energy development and use has had a significant impact on carbon emission reduction.

5. Future Guarantee of China's Wind and Solar Energy Resources Development and Utilization

5.1. The Service Ability of Regional Climate Information under Different Time Scales

According to the IPCC report, recent years have seen global climate anomalies, with indications of regional climate collapse emerging [3]. For example, the drought event in the Yangtze River Basin (2022), the extreme rainstorm event in Zhengzhou (2021), and the extreme typhoon event (2023). Consequently, the spatiotemporal evolution of future extreme weather and climatic events—such as rainstorms, flood disasters, typhoons, thunderbolts, droughts, and snow disasters—exhibit distinct seasonal and regional characteristics. These characteristics will directly expose wind farms and photovoltaic power plant equipment in the region to meteorological risks [82,83]. For instance, continuous high and low temperatures can lead to increased power system load, reduced photovoltaic module power generation efficiency, and shortened battery life. Extreme temperatures and thunderstorms may also impact the operation of wind turbines. Furthermore, weather with strong dusts can affect the acceptance rate of solar radiation, decrease component power generation, and increase power generation costs [82,83].

Meanwhile, future combined climate disaster risks induced by climate change will pose significant challenges to the development and supply–demand balance of wind and solar energy [84,85]. For example, four types of compound extreme events exist in the Chinese region (compound hot extremes; compound dry-hot extremes; compound wet-hot extremes; and compound flooding). Therefore, in the phase of wind and solar energy development and safe operation, it is imperative for the Chinese government to enhance its technical capabilities in climate monitoring and prediction and its impact on resource development and safe operation. To ultimately improve resource development and utilization efficiency, it is necessary to analyze climate change at different time scales, enhance the development and utilization of wind and solar energy, promote peak adjustment and peak shifting of wind power and photovoltaic power generation, and improve the intelligence level of the power grid.

5.2. Prediction Techniques for High-Resolution Spatiotemporal Datasets

Wind and solar resources, as typical climate assets, require high-resolution spatiotemporal data sets to ensure the accurate evaluation of their future development potential [84,85]. However, current predictive research predominantly concentrates on the fluctuations in wind speed and solar radiation. There is a notable dearth of future prediction studies concerning China's wind and solar energy resources, particularly those examining the contribution of their development and utilization to carbon emission reduction under prospective carbon neutral scenarios.

Moreover, daily or monthly scale data encompass numerous pivotal wind and solar signals. Consequently, these datasets fail to capture the instantaneous and localized evolution of wind power and photovoltaic technology development without the incorporation of high spatiotemporal resolution (hourly) data [61]. Hence, precise forecasting of future wind and photovoltaic power generation holds significant implications for power system scheduling, load coordination, regional wind and solar complementarity, conventional energy generation planning, and wind and photovoltaic power generation planning [86].

5.3. The Coordinated Development of Industrial Planning and Development Technology

Significant seasonal and regional variations exist in the development and utilization of wind and solar energy resources in China. Compared to solar energy, wind energy exhibits greater seasonal and regional disparities [20–22]. In most regions, spatial scale can be expanded through regional coordination to alleviate the instability of power generation and output caused by climate and geographical conditions [65,66]. Furthermore, a multi-energy complementary power generation model can be developed by leveraging hydropower resources and adjusting the proportion of power generation based on the different distribution characteristics of wind and solar energy in the region. This model can minimize the impact of extreme weather, climate, and unique geographical environments on the capacity of new energy power generation facilities (Figure 5) [7]. However, in the context of the increasing installed capacity of clean energy such as water, wind and light, how to coordinate scheduling to deliver high-quality electric energy to the grid is the difficulty of multi-energy complementarity. As a good power source for large-scale regulation, hydropower can effectively smooth the fluctuations of wind power generation and photovoltaic power generation, and improve the ability of the grid to absorb it. Therefore, it is very important to accurately analyze the operation characteristics of complementary wind–water scheduling [83,87].

In the future, the multi-objective joint dispatching operation of water–wind–solar will continue to play an important role, and, with the continuous improvement of technology, a more efficient energy management mode will be attainable [86]. Therefore, researchers will need to constantly explore more effective multi-objective scheduling algorithms to better meet the needs of the multi-objective combined scheduling operation of water–wind–solar energies. In general, the multi-objective combined operation of water–wind–solar energies is an energy management method with broad prospects, which is of great significance for maximizing the utilization of renewable energy, improving the stability and reliability of energy systems, reducing the impact on the environment, and improving the economic benefits of renewable energy. There are still many challenges in the practical application of water–wind–solar multi-objective joint scheduling. For example, how to effectively deal with the instability of renewable energy to ensure the stable and reliable operation of the system is an important issue [7]. Therefore, scientific planning of power system scheduling schemes, improving the utilization efficiency of the new power system, reducing abandoned power, and developing wind and solar resource technologies are crucial measures for enhancing the development potential of China's wind and solar resources and reducing urban carbon emissions.

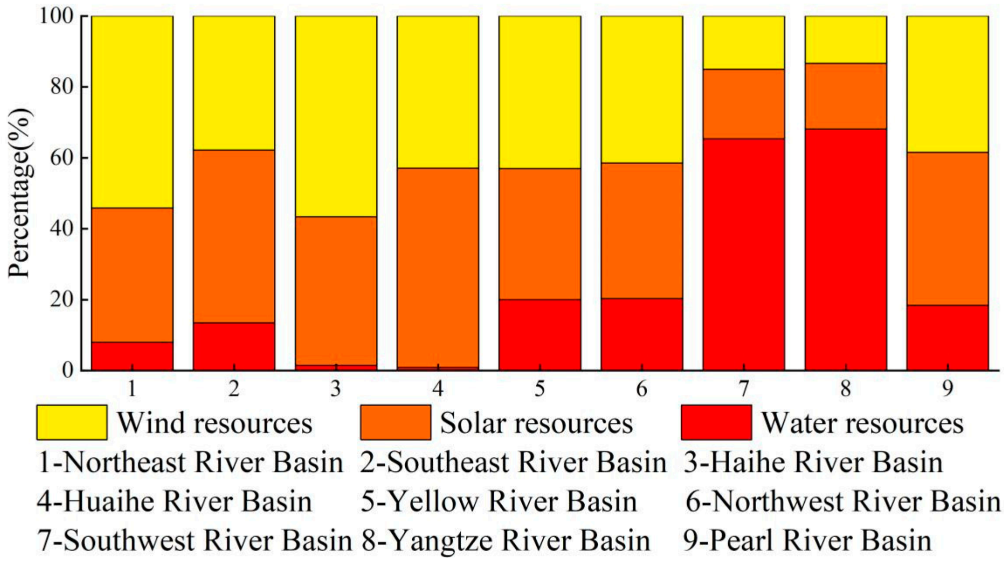

Figure 5. Percent of wind, hydro, and solar energy resources in the nine river basins of China. (Note: Data cited in Lv et al., 2022 [7]).

6. Summary and Prospect

In the context of global warming, the most effective strategies for reducing greenhouse gas emissions currently involve decreasing fossil energy consumption and increasing the use of clean, renewable resources. Wind and solar energy are typical climate resources that exhibit significant intermittency and volatility in time scales. China is rich in wind and solar energy resources; however, their development and utilization are subject to seasonal and regional variations. Meanwhile, government policies and regulatory measures have been instrumental in the evolution of the wind and solar industry.

To enhance the efficiency of renewable energy development and utilization, numerous scholars and local governments have proposed and initially implemented a model for the complementary development of wind and solar energy on a regional time scale. However, further research findings and case studies indicate that this mode of complementary development is not universally applicable due to technical limitations and varying climate resource characteristics. The profitability derived from the actual complementary development of these two resources may be less than anticipated. Consequently, advanced power storage technology, power transmission technology, and multi-energy complementary development methods represent the primary avenues for improving the development and utilization of renewable energy.

From a resource quantity standpoint, hydropower resources represent the most mature form of clean energy currently developed and utilized. To optimize the profitability derived from the combined development of various renewable resources, we can leverage hydropower resources to harmonize their complementarity (Figure 5). However, in practice, it is challenging to align the complementary development of wind and solar energy with hydropower resources. The current exploitation of hydropower resources is predominantly constrained by fresh water availability. Future research must address the challenge of quantitatively assessing and integrating wind and solar energy using hydro or other renewable sources in regions where such complementarity is minimal.

In addition, the development and utilization of wind and solar energy requires a wide area of land resources, which leads to wind blade rotation and photovoltaic panels having a greater impact on the ecological environment (such as limiting the growth of vegetation around the power plant, reducing the living space of animals, etc.). However, from the perspective of the overall ecological environment, the economic benefits and ecological effects brought by the development and utilization of wind and solar energy are enough to make up for the current ecological loss. In the current context, the development and utilization of wind and solar energy resources is still an effective means to maximize environmental benefits.

Author Contributions: Conceptualization, T.L.; methodology, A.L. and T.L.; software, A.L. and T.L.; validation, T.L. and Y.L.; formal analysis, A.L. and T.L.; investigation, T.L. and Y.L.; resources, A.L.; data curation, A.L. and T.L.; writing—original draft preparation, A.L.; writing—review and editing, A.L..; visualization, A.L. and T.L.; supervision, A.L.; project administration, A.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Third Xinjiang Scientific Expedition and Research Program (2021xjkk0203).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author (lvaf@igsnrr.ac.cn).

Acknowledgments: We thank the editor and anonymous reviewers for their very helpful comments and suggestions for improving the quality of the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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