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SWOT Analysis of Wind, Hydro, and Solar Energy Power Generation: Applications and Future Development in China

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Abstract: China is currently undergoing a transition in its energy structure, gradually reducing reliance on fossil fuels and increasing the proportion of clean energy sources. The government actively promotes the development of renewable energy, such as wind and solar power, while encouraging technological innovation to enhance energy efficiency. Additionally, China is exploring and promoting new energy technologies like nuclear and hydrogen power to establish a greener and low-carbon energy system in line with sustainable development goals. This paper provides a comprehensive analysis of the current status of wind, solar, and hydro energy in China using a SWOT analysis approach. It examines the strengths, weaknesses, opportunities, and threats associated with each energy source, focusing particularly on their environmental impacts, technological hurdles, and resource distribution. Wind power stands out as an essential element within China's renewable energy mix due to its substantial potential for power generation capacity - ranking second globally. However, it confronts concerns regarding its environmental implications as well as output variability. Solar energy has advantages in directing solar power conversion and easy recycling; it exhibits promising prospects. But encounters conflicts related to land use and efficiency issues. Hydropower continues to be a major contributor; nevertheless, it poses ecological and social challenges. Furthermore, this paper scrutinizes China's leadership in renewable energy while offering recommendations for sustainable development and policy improvements that can facilitate its ongoing transition towards cleaner sources of power.

Keywords: Renewable energy, wind power, solar energy, hydropower, China energy transition

1. Introduction

As global climate change intensifies and the demand for energy keeps rising, clean and renewable energy has become a central focus of the international community. Wind energy, solar energy, and hydro energy, as key components of renewable energy, have gained prominence in the global energy landscape due to their abundance and low-carbon nature. Despite the advantages of these three energy sources, they face challenges such as uneven resource distribution, technological bottlenecks, and environmental impacts. This review conducts a comprehensive SWOT analysis of wind energy, solar energy, and hydro energy in order to evaluate their current status and environmental impacts in China while also providing insights into their future prospects. It delves

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into the potential for these energy sources to play a greater role in China's energy transition, offering practical recommendations for policymakers and industry stakeholders.

The SWOT analysis is a vital tool employed by organizations to evaluate internal strengths and weaknesses, as well as external opportunities and threats. Internal strengths refer to factors that assist in achieving objectives, while weaknesses impede success. External opportunities encompass favorable conditions and chances to bridge gaps or embark on new ventures, supporting goal attainment. On the other hand, threats are external elements that have the potential to hinder an organization's progress towards its goals [1]. By utilizing the SWOT analysis, this paper aims to comprehensively explore the pros and cons of three energy sources, particularly their adverse impact on the environment. Additionally, it will provide practical recommendations backed by credible sources for future implementation of these energy sources in China.

2. New energy generation method based on SWOT analysis

2.1. Wind power generation

Reaching a staggering 651 GW of electricity generation globally, wind turbines secure the runner-up spot just behind hydropower [2]. The substantial renewable energy production from these turbines plays a crucial role in curbing carbon emissions. Additionally, the construction cycle for wind power projects is relatively short, typically taking only a few months to a year to complete and become operational [3]. In addition, the installation scale of wind power is flexible, enabling adjustments based on actual needs, ranging from small distributed generation to large wind farms, thus accommodating various application scenarios. However, there are still several negative environmental impacts of wind turbines. The noise generated during the installation and maintenance of wind turbines is a concern. And there is the potential for large accidents during storms. Additionally, the fluctuation of wind speeds leads to variations in output power, presenting a challenge for consistent energy supply [4].

Despite these weaknesses, opportunities for wind energy are ample, with turbines capable of being installed both onshore and offshore. Furthermore, their aesthetic value can be utilized to improve the visual appeal of plains. Nonetheless, threats to the environment and wildlife persist, including the occasional fatality of birds due to collisions with blades [5]. Offshore installations can disturb the seabed, impacting biodiversity and altering benthic habitats. Electromagnetic fields may disrupt communication between marine mammals, and debris along with lubricating oil can contaminate the surrounding environment. Moreover, the establishment of wind farms often requires deforestation, potentially leading to soil erosion [5].

Table 1: SWOT analysis of wind power plants

Strength	High power generating capacity; Easy construction and recycling
Weakness	Noise pollution; Various output due to wind speed changes
Opportunity	Flexible installation (offshore/onshore); Aesthetic potential
Threat	Biodiversity impact; Environmental and marine disruption;

2.2. Solar power generation

The primary focus of this paper is to investigate the photovoltaic power generation system, which involves the utilization of solar panels combined with an inverter and various electrical and mechanical components. These components harness energy from sunlight to produce electricity.

On the one hand, the utilization of solar collectors in numerous European countries at the level of family farms and households has been instrumental in reducing domestic energy costs and, in many

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instances, achieving energy self-sufficiency [6]. Furthermore, solar power generation has the capability to utilize sunlight and transform it into electrical energy directly. This implies that a photovoltaic (PV) system can generate electricity without relying on any components in motion. The maintenance expenses associated with PV systems are comparatively lower than those of numerous other renewable energy sources (RESs), while also offering long-term service. The design of the system is straightforward, capable of producing microwatts of power in individual setups and scaling up to megawatts when integrated into extensive networks [7].

On the other hand, the establishment of solar farms is not without its challenges. The concrete structures necessary for angling PV panels into the soil can disrupt the soil's heat and water distribution, negatively impacting soil productivity and the potential for vegetation to regenerate once the PV panels reach the end of their lifespan. Moreover, utility-scale PV installations require large land areas, ranging from 3.5 to 10 acres, which could diminish arable land, although the use of sites such as abandoned mining areas or contaminated brown fields is encouraged [8]. Additionally, the extraction of solar energy can harm surrounding vegetation, leading to an increase in dust that reduces the efficiency of solar panels by blocking solar radiation, as observed in Egypt, where power generation was decreased by 35% due to dust accumulation [9]. This dust not only degrades the performance of the solar panels but also worsens air quality, raising health concerns. Moreover, during the whole lifetime, around 32–82 g/kWh CO_2 gets released in the environment [10]. In addition, PV also has a certain pollution to water; solar photovoltaic panels contain toxic elements such as lead and cadmium, which can contaminate water resources if not managed properly during production and disposal. When PV panels corrode, break, or are improperly disposed of, these toxic substances can leach into the environment. As panels degrade, metals like zinc, copper, nickel, and lead can enter the groundwater, posing pollution risks [11, 12]. In addition to the impact on human beings, solar PV also has an impact on the local ecological environment and animals; it can negatively impact local habitats, as seen in California's Mojave Desert, where tortoises and burrowing owls rely on burrows for shelter. Building solar farms displaces these animals, making the area uninhabitable for the local flora and fauna [13].

Table 2: SWOT analysis of solar power generation

Strength	Reducing energy costs; Direct conversion; Low maintenance
Weakness	Soil degradation; Dust affecting efficiency; CO_2 emissions
Opportunity	Easy to design and able to decorate the roof
Threat	Soil disturbance; Air and water contamination; Habitat disruption

2.3. Hydro power generation

Hydroelectric power is generated through the construction of a dam across a flowing river. By releasing water from higher elevations, it descends onto the hydroelectric turbine's blades, generating electricity. Hydroelectric power systems have been extensively researched and are among the earliest forms of renewable energy.

On the one hand, hydroelectric power generation boasts several significant advantages, including a longer lifespan of 50 to 100 years, which surpasses that of other renewable energy sources (RESs) [14]. Additionally, the potential for hydroelectric power is perpetually available due to the natural water cycle. Moreover, it has the highest power-generating capacity among RESs, reaching up to 1150 GW, making it a highly reliable and efficient form of renewable energy [2].

On the other hand, dams have been shown to have adverse effects on aquatic life. While technologies like fish ladders are in place to facilitate fish migration upstream for spawning, the turbine blades continue to impact numerous species. Fish populations are particularly susceptible to

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the dangers posed by the rotating blades of turbines. Studies have indicated that an approximate mortality rate of fish, ranging from 5 to 10%, is consistently observed as a consequence of their encounters with these turbine blades during their migration patterns or while swimming near power generation facilities.

[15] Additionally, the still nature of reservoir waters leads to a buildup of excessive nutrients, sediments, and weeds, which can result in eutrophication near the surface of the reservoir. It is imperative to implement careful strategies to remove these surplus weeds [16].

Hydroelectric plants emit greenhouse gases during all stages of their life cycle, with emissions ranging from 4.5–13.61g to 27.2g CO_2 eq./kWh, depending on plant size and location. In tropical and peatland areas, emissions are higher due to vegetation and soil decomposition, with lifecycle emissions estimated at 226.8g CO_2 eq./kWh [2]. Organic matter accumulation, CO_2 and CH_4 release, and downstream oxidation contribute to hydropower's ecological footprint.

Table 3: SWOT analysis of hydro power generation

Strength	Long lifespans; Natural availability
Weakness	Challenging siting; Large land use; Impacting fish and water quality
Opportunity	Emission Reduction via advanced drilling methods
Threat	Land transformation; Aquatic habitat disruption

3. The current situation analysis of three power generation energies in China

As shown in Figure 1, the evolution of China's non-combustion renewable electricity generation sources since 2000. From the chart, it can be seen that hydropower has always dominated, with its output being the highest among all renewable energy types and showing a trend of steady growth year by year. The output of wind power and solar photovoltaic power is also gradually increasing, but it is still lower than hydropower.

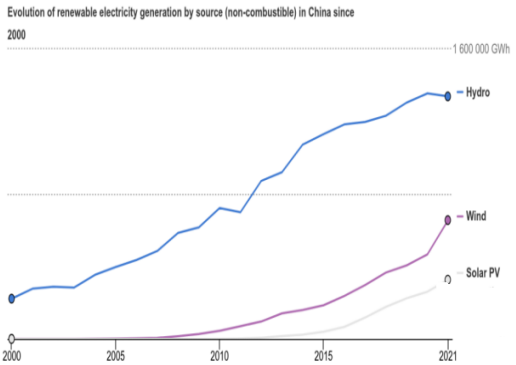

Figure 1: Evolution of renewable electricity generation in China since 2000 [17]

Figure 2 shows the distribution of China's non-fossil fuel renewable electricity generation sources in 2021. According to the data, hydropower accounted for 57.6% of the total generation, followed by wind power at 28.2% and solar PV at 14.1%. Tidal, wave, oceanic, and geothermal energy contributed less than 0.01%.

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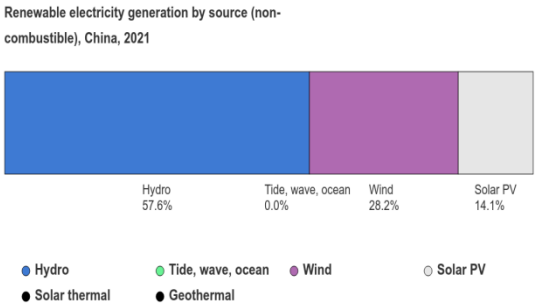

Figure 2: Renewable electricity generation by source, China, 2021 [19]

With the global PV market transitioning from Europe to Asia, China has emerged as both the largest and fastest-growing country in the solar energy industry [18]. Since 2010, when China surpassed other nations to become the largest in terms of wind power installed capacity (WPIC), it has maintained its leading position in both new and cumulative WPIC globally, with 2018 being no different. In that year, China's cumulative WPIC constituted 35.73% of the world's total, marking four consecutive years where it has accounted for over one-third of the global WPIC. China has emerged as an essential driver in the advancement of the worldwide wind power sector [19]. Lastly, China's hydropower system has seen rapid growth to accommodate the country's large energy needs. With over 330 GW of installed capacity, it contributes approximately 20% to the nation's total electricity production, leading globally in hydropower generation [20].

4. Future trends

4.1. Future development potential and suggestions of wind energy in China

In alignment with China's ambition to attain the economic stature of a moderately developed nation by 2050, the projected energy demand is anticipated to soar to 1.5 billion kilowatts, underscoring the immense untapped potential of hydropower development within the country. Consequently, it is both prudent and imperative to prioritize and bolster the development of hydropower resources. Additionally, the proliferation of small hydropower initiatives in rural sectors, leveraging the nation's abundant and widely distributed small hydropower resources, promises substantial economic rewards while propelling the modernization of China's countryside. These initiatives not only yield significant environmental and societal benefits but also act as a bulwark against the migration of urban environmental pollution to rural areas, holding vast potential and broad developmental prospects.

Addressing the challenges posed by hydropower development, particularly the resettlement of displaced communities, requires a dual-pronged strategy. Initially, it is essential to implement structured planning and refine systemic frameworks, ensuring the execution of integrated river basin planning and unified water resource management that prioritize ecological health, investment returns, and public engagement. Furthermore, the advancement of hydropower projects should be complemented by a shift from mere financial compensation to a more holistic approach that transforms land rights into capital investment, thereby safeguarding the rights and welfare of those affected by resettlement. This comprehensive strategy not only addresses the immediate concerns of displaced communities but also integrates them into the broader narrative of sustainable development, ensuring that the journey towards a robust hydropower sector is inclusive and considerate of all stakeholders.

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4.2. Future development potential and suggestions of solar energy in China

Despite its relatively low solar potential, the western region of China possesses favorable conditions for large-scale photovoltaic (PV) installations due to its abundant solar radiation and sparse population. In order to fulfill its commitments to the Paris Agreement and the "13th Five-Year Plan," China has implemented policies aimed at boosting renewable energy, with a specific focus on significantly increasing solar PV installations by 2030. This study aims to analyze the spatial and temporal distribution of solar radiation in China and assess the potential for PV power generation, providing valuable insights for the development and management of PV systems. The west, characterized by higher levels of solar radiation, offers more advantageous conditions for PV power production compared to the eastern part of China. The construction of solar PV plants requires substantial land for panel installation, which can be easily accommodated in the expansive and sparsely populated areas found in western China. A case study conducted in northwest China highlights this region's significant potential for developing PV power plants due to intense solar radiation levels combined with high altitude. It is estimated that approximately 39% of China's total land area is suitable for large-scale PV installations, with over 70% of these areas located in western regions that boast excellent geographic potential thanks to their gentle slopes, limited vegetation cover, and rich resources of solar radiation.

In a depth study of China's solar photovoltaic (PV) power potential in seven province in China, which gives several key recommendations for optimizing the future performance of PV farms. Firstly, developing and utilizing high-efficiency solar cells should be a priority to enhance energy conversion rates. Secondly, improving the design of array spacing is essential to minimize inter-row shading, maximizing the solar radiation each panel receives. Additionally, reducing solar power curtailment is crucial for increasing overall energy output. Implementing these strategies can effectively boost the actual power generation of solar PV systems, bridge the gap with technical potential, and ultimately improve land-use efficiency by making better use of limited resources. These suggestions not only guide advancements in solar PV technology but also inform policy-making for more efficient and sustainable energy development.

4.3. Future development potential and suggestions of hydro energy in China

Behind China's hydropower system’s today achievement lies the unique characteristics of China's hydropower system: it is not only vast in scale but also spans multiple basins and regions, forming an intricately interconnected network. However, these features also present a series of challenges, particularly the sharp increase in system dimensions, which complicates model building and optimization. Specifically, the operation of the hydropower system exhibits high-dimensional characteristics, with parameters such as installed capacity, reservoir storage, and head increasing due to technological advancements, leading to a surge in the number of decision variables. Additionally, the non-linearity of the hydropower system is pronounced, and the hydraulic connections between reservoirs result in tight spatiotemporal coupling within the system. The complexity is further amplified by the multiple scheduling requirements for power generation, flood control, and water supply. Moreover, hydropower operations are subject to uncertainties such as natural inflows and load demands. In the face of these challenges, future optimization strategies will need to adopt a multidimensional approach: leveraging knowledge management to reduce modeling complexity, utilizing high-performance computing to enhance execution efficiency, employing spatial identification techniques to avoid unnecessary computational burdens, improving search mechanisms to boost algorithmic performance, and exploring innovative methods and technologies to provide creative solutions. The implementation of these strategies aims to increase the efficiency

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and reliability of hydropower system operations while supporting China's goals of energy structure adjustment and reducing the proportion of non-fossil energy in primary energy consumption [20].

5. Conclusion

This paper provides a comprehensive SWOT analysis of wind, solar, and hydro energy in China, identifying their strengths, weaknesses, opportunities, and threats. Despite its global importance and flexible installation options, wind energy faces challenges such as environmental disturbance and inconsistent power generation. Solar energy has the potential to reduce household energy expenses, but conflicts over land use, efficiency losses, and accumulation of dust hinder its growth. Hydropower plays a significant role in China's energy production; however, it poses ecological and social concerns primarily due to dam construction and disruption of habitats. The limitations of this study include a reliance on older literature and a lack of in-depth exploration into emerging technologies and policy frameworks. Future research should focus on improving energy storage systems to address the intermittent nature of renewables, developing more efficient energy conversion technologies, and minimizing the environmental impact of energy production. Addressing these areas will be critical to advancing China's renewable energy sector and ensuring its continued leadership in global climate action.

In conclusion, while wind, solar, and hydro energy are crucial to China's energy transition, significant challenges must be addressed to ensure their sustainable development. Technological innovations are necessary to improve efficiency, mitigate environmental impacts, and enable large-scale deployment. Additionally, supportive policies are essential to enhance renewable energy adoption and reduce the reliance on fossil fuels. China's ability to lead the global renewable energy market hinges on overcoming these obstacles.

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