RESEARCH ARTICLE | NOVEMBER 17 2022

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AIP Conf. Proc. 2681, 020074 (2022)
https://doi.org/10.1063/5.0127241

Review of Renewable Energy Curtailment in China: Current Situation and Solutions

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Abstract. In recent decades, China's renewable power generation has developed quickly. However, the randomness of output power causes wind and photovoltaic power curtailment. With the rapid development of renewable energy, renewable energy consumption has gradually become the focus of research. This article comprehensively reviews the current situation and practices of reducing the curtailment of renewable energy in China. From the perspective of methods used to stabilize the fluctuation characteristics of generation output, two modes are outlined: based on energy storage devices and complementary wind-solar system. Then, an Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) system simulation model is proposed as a crucial solution to reduce renewable energy waste. Finally, the application and development trend of renewable energy and energy storage technology has prospected.

INTRODUCTION

In recent years, the lack of fossil energy and the gradually emerging environmental protection concept has prioritised clean energy resources. Solar and wind power are the most convenient, widespread, and commercially accepted among all the clean energy resources. According to information from the China Meteorological Administration, the potential power generation capacity of onshore wind energy resources at an altitude of 10m is about 3.226 billion kilowatts, of which 7.8% is available for exploitation [1]. In addition to the similar degree of abundance, the two resources are similar and uneven in the distribution in Figs. 1, 2 [2,3].

According to the International Energy Agency data, China was still the largest importer with 3.09 million tons of coal purchases in 2020[4]. China is adopting a series of measures to speed up equipment related to renewable energy and reduce coal demand.

Over the last decade, there has been rapid growth in the clean energy power generation of electricity in China. In 2010, China's total installed wind energy equipment accounted for 48.1% of the world's share, and the rank also rose to the forefront[5]. China became the leading nation of wind power applications. From 2016 to 2020, the average yearly growth rate of wind power equipment in use is 16.9%. In 2020, wind power and photovoltaic power supply of 727 billion kWh or 9.5% of national electricity consumption.

In addition, the relevant industries of clean energy have also developed rapidly. According to data, the 2020 World Wind Power has a capacity of 78.94 GW[6]. A total of 7 companies in our country entered TOP10, and its installed capacity reached 45.36 GW. Specifically, Jinfeng Technology has reached 13.06GW in 2020 new installed capacity ranking second. Regarding the photovoltaic industry, Chinese companies play a significant role in the world's relational energy industry. Longji Green Energy Technology Co., Ltd. is ranked first in a revenue of 4716 million US dollars.

This article introduced the abandonment of wind and solar and summarized the solutions. First, it describes the situation of abandonment of wind and light and the distribution of various regions and found differences in the

3rd International Conference on Energy and Power, ICEP2021
AIP Conf. Proc. 2681, 020074-1–020074-7; https://doi.org/10.1063/5.0127241
Published by AIP Publishing. 978-0-7354-4257-3/$30.00

distribution of resources and the status of wind abandonment in different regions. Then, it introduced the leading solutions. The last model of the Advanced Adiabatic Compressed Air Energy Storage System (AA-CAES) is introduced.

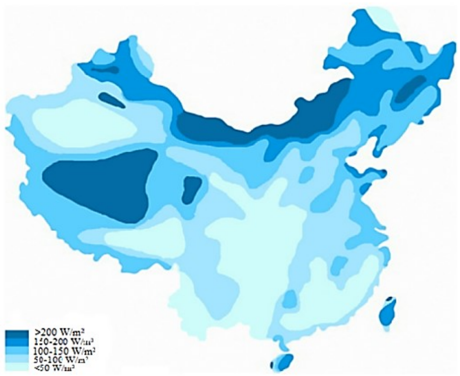

FIGURE 1. Distribution of wind resources in various regions.

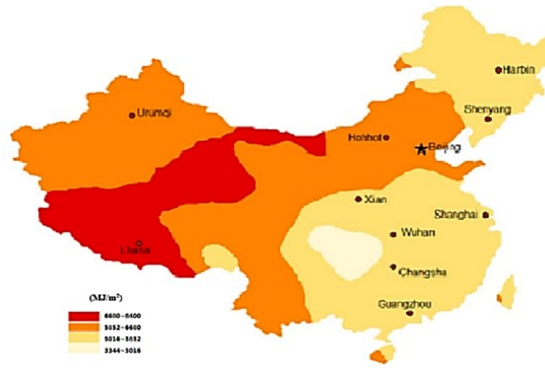

FIGURE 2. The annual radiation intensity of solar energy resources in various regions.

SITUATIONS OF WIND AND SOLAR ENERGY CURTAILMENT AND REGIONAL CHARACTERISTICS

The traditional fossil energy-based power generation structure is not sustainable because fossil fuels will increase carbon emissions [7]. Therefore, renewable energy power generation has been rapidly developed worldwide. However, with the rapid growth of renewable energy, the abandonment of wind and solar in some areas of my country has become more serious [8]. The failure of renewable energy capacity has led to the curtailment of renewable energy power generation. In recent years, China's average wind curtailment rate has reached 15%, while the average wind curtailment rate of photovoltaics in Northwest China is as high as 30%.

China’s installed wind power and photovoltaic capacity have reached 220GW, and 80GW (1GW = 1000MW) ranked first globally, but electricity generation is not the first. For example, wind power installations in the United States Capacity is only 58% of China’s grid-connected wind power installed capacity, but its wind power is 200 TW/h, which is higher than China’s 201TW/h [9]. One of the reasons for the large installed capacity and relatively small power generation is massive curtailment. Related statistics show that the curtailment rate of wind and photovoltaic in China in 2020 was 15% and 12.6%. Due to the stagnant economic development of Gansu, Xinjiang, Inner Mongolia, and other places rich in renewable energy, the local absorption capacity was limited, and the construction of transmission lines could not keep up with the power plants. The speed of construction in these areas becomes the key affect factor. The “wind curtailment rate” reached 39% and 32% in Gansu and Xinjiang provinces, and the “light curtailment rate” reached 30.7% and 26%. [10-11]. China's installed renewable power capacity reached 934 billion kilowatt-hours in 2020, accounting for 5 percent of total electricity consumption. However, the power supply and demand picture vary from region to region, shown in Table1.

It can be concluded from Table 1 that in the northeast and northwest of China, the annual supply of electric power exceeds the demand, resulting in severe wind and solar energy curtailment in these two regions. Most of the rest of the country is in balance or excess demand for electricity, so there is no wind and solar energy curtailment.

Among the 31 provinces in China, only 13 provinces have a renewable energy capacity higher than the average level. Among these provinces, Yunnan Province ranked first with 85.7% of the accommodation, Tibet Autonomous Region ranked second with 84.4%, Qinghai Province ranked third, and renewable energy accommodation accounted for 70% of its total electricity consumption.

TABLE 1. Electric power supply and demand by region in China from 2016 to 2020

	2016	2017	2018	2019	2020
North China	balance	almost balance	excess demand for electricity	excess demand for electricity	almost balance
East China	balance	excess demand for electricity	almost balance	almost balance	balance
Central China	balance	almost balance	excess demand for electricity	almost balance	almost balance
Northeast China	oversupply	oversupply	oversupply	oversupply	oversupply
Northwest China	oversupply	oversupply	oversupply	oversupply	oversupply
South China	oversupply	oversupply	almost balance	almost balance	almost balance

RESEARCH HISTORY AND STATUS QUO OF RENEWABLE ENERGY AND ENERGY STORAGE SYSTEMS

With the finiteness of conventional energy and the increasingly major resource problems, renewable energy has received more and more attention. In 2020, China vigorously advocated the development and utilisation of wind power and photovoltaic resources. As of the end of 2020, The cumulative installed capacity of photovoltaic power generation nationwide reached 253GW, an increase of 23.5% compared to last year, and the growth rate has rebounded. Despite the pandemic, China has ranked first in the world in installed renewable power generation capacity for six consecutive years. However, due to the unstable power generation of renewable energy and low user demand, large waste areas have also been caused [12]. In 2020, the utilisation rate of photovoltaic and wind power is around 95%. To further increase the utilisation rate and reduce waste, China has made many efforts. At present, the leading solutions can be divided into two categories, one is to use energy storage devices [13-16], and the other is based on the principle of energy complementarity. This part mainly introduces these two modes [17].

Overview of China's Main Energy Storage Technologies

Energy storage devices are used to reduce the instability of photovoltaic and wind power generation, store energy when power is sufficient, and release energy when power is insufficient. 2016-2020 China's installed capacity of energy storage power plants is shown in Fig. 3. Fig.4 shows the distribution of installed capacity of energy storage projects in China.

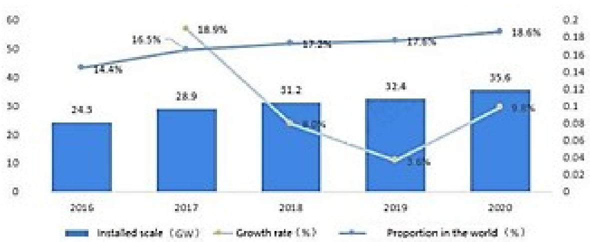

FIGURE 3. Installed capacity of China's projects in operation in 2020

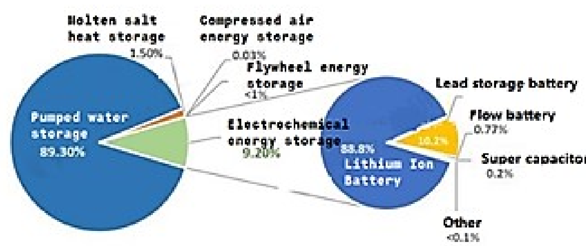

FIGURE 4. Installed capacity China's energy storage power plants (2016 to 2020)

The installed capacity of China's energy storage power plant was 35.6GW by the end of 2020, registering a year-on-year increase of 9.8%. The percentage of pumped energy storage was the biggest, and it was 89.30%, followed by electrochemical and battery energy storage with an installed capacity of 3.28GW, accounting for 9.2%. It is expected that the installed capacity of pumped energy storage will maintain a growth rate of more than 15% over the next five years, and the installed capacity will be 74GW by 2026.

Overview of the Complementary Characteristics of Different Generation Systems in China

According to the classification of the existing energy complementary models in China, it can be divided into the following categories [18] : (1); The first model is based on energy storage devices. Wind-PV-storage consumption mode has been introduced in detail in 3.1. (2) By establishing a flexible micro-grid system, a large number of small-scale wind and photovoltaic power generation within a particular area, thereby improving energy utilization and reducing the environmental pollution. It has been widely used in remote mountain villages, schools, and other places in China. (3) Unstable photovoltaic power generation and solar power generation are directly input to the grid. The technology is mainly based on the power plant's load regulation capability. This approach has become the mainstream model in China. (4) In some areas with significant renewable energy generation capacity, if renewable sources are directly integrated into the grid on a large scale, it will affect the stability of the local grid, so peak shaving is required before grid connection. It is the most effective solution for large-scale power grid integration. (5) In some areas with abundant water resources. Hydropower can be used for peak shaving, this model is still in its infancy, and supporting facilities need further improvement.

ADVANCED ADIABATIC COMPRESSED AIR ENERGY STORAGE (AA-CAES) SYSTEM

Brief of AA-CAES system

AA-CAES is an emerging technology of large-scale energy storage which can solve the unstable of renewable energy and the difficulties of grid connection. AA-CAES mainly consists of compressors, turbines, heaters, thermal energy storage. During the energy storage stage, the air in the atmosphere is compressed by the compressor to exchange heat with the heat exchanger. The compression heat is stored in the thermal energy storage, and the high-pressure gas is stored in the gas storage tank [19]. The system structure is shown in Fig.5. and components parameters and calculation formula are shown in Table 2.

The thermal energy storage (TES) medium generates heat during the energy release phase and preheats the high-pressure air. The AA-CAES system uses TES instead of the traditional combustion chamber, thereby improving system efficiency, and reducing energy loss and pollutant emissions.

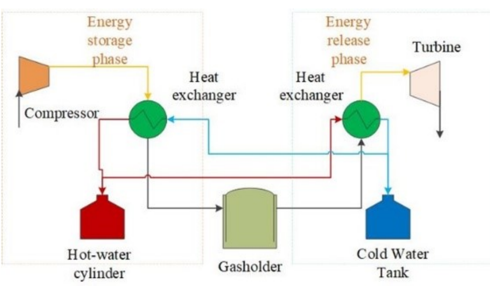

FIGURE 5. AA-CAES system

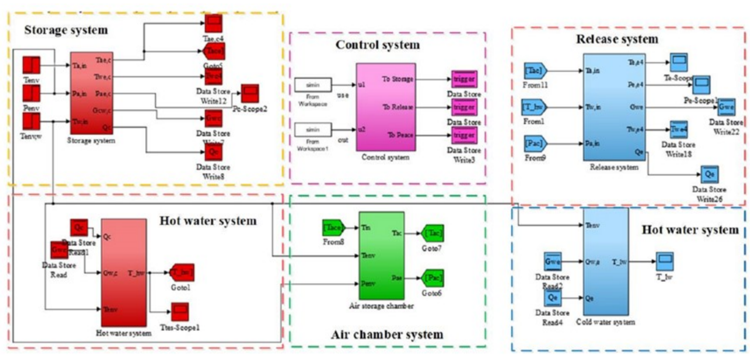

FIGURE 6. 1.5MW AA-CAES simulation model diagram

TABLE 2. AA-CAES components parameters and calculation formula.

Component	Parameter	Auxiliary equations	Remarks
Compressor	exhaust temperature of air in i-th compressor	$T^{e}_{c,i} = T^{i}_{c,i}\left[1 + \frac{\beta_{c,i}^{\frac{k-1}{k}} - 1}{\eta_{cs}}\right]$	$T^{i}_{c,i}$ is the inlet temperature of the air in i-th compressor η_{cs} is the efficiency of the compressor $\beta_{c,i}$ is the compression ratio of the i-th compressor κ is the polytropic index.
	consumed work of the i-th compressor	$w_{c,i} = c_p T^{i}_{c,i} \frac{\beta_{c,i}^{\frac{k-1}{k}} - 1}{\eta_{cs}}$	
Heat exchanger	effectiveness	$\varepsilon = \frac{T^{e}_{a} - T^{i}_{a}}{T^{i}_{w} - T^{i}_{a}}$	The subscripts a and w represent air and water, respectively. The superscript e and i represent exhaust port and the inlet port.
	inlet air temperature	$T^{i}_{ca} = \varepsilon T^{i}_{cw} + (1-\varepsilon) T^{e}_{ca}$	T^{i}_{cw} is the inlet temperature of water in the heat exchanger. T^{e}_{ca} is the temperature of exhaust air.
	pressure loss	$\Delta P = P^{i}_{a}(\frac{0.0083}{1-\varepsilon}\varepsilon)$	P^{i}_{a} is the inlet air pressure of the heat exchanger of the i-th compressor.
	inlet air temperature	$T^{i}_{ta} = \varepsilon T^{i}_{cw} + (1-\varepsilon) T^{e}_{ta}$	T^{e}_{ta} is the temperature of the turbine
	outlet water temperature of the i-th turbine	$T^{i}_{c,i+1} = \varepsilon_c T^{i}_{cw,i} + (1-\varepsilon_c) T^{e}_{c,i}$	
Turbine	outlet temperature of the i-th turbine	$T^{e}_{e,i} = T^{i}_{e,i}[1 - \eta_{es}(1 - \beta_{e,i}^{\frac{1-\kappa}{\kappa}})]$	$T^{i}_{e,i}$ is the inlet temperature of the i-th turbine η_{es} is the turbine efficiency, $\beta_{e,i}$ is the compression ratio of the i-th turbine
	output power at time t of the i-th turbine	$P_{t,i} = m_{t,a} c_{p,a}\left(T^{i}_{e,i} - T^{e}_{e,i}\right)$	

AA-CAES system construction

The construction of the AA-CAES in this paper is based on the structural model of the 1.5MW AA-CAES demonstration power station of the Chinese Academy of Sciences. The energy storage power station operating data in this paper is used as the design data, and the 1.5MW basic model is established and verified. When the established model has satisfying reliability, a 10MW AA-CAES is constructed by adjusting the system parameters based on the 1.5MW model structure. The modular modelling method is used in the model building process. The modular modelling is shown in Fig.6.

In this model, parts of the storage, hot water, and release systems refer to Table 2, and the remaining parts refer to [20]. The AA-CAES system includes four-stage compression and four-stage expansion, using inter-stage cooling and inter-stage heating. The setting parameters are given in [21]. Finally, the parameters of the 1.5MW-level AA-CAES energy storage system model that has been established and verified above are adjusted. The MATLAB/Simulink model of the 10MW-level energy storage system is established. The 10MW energy storage system constant-coefficient value parameters are shown in Table 3.

TABLE 3. 10 MW storage system constant-coefficient value parameters.

Stage	Energy storage				Release energy			
Series	1	2	3	4	1	2	3	4
Air density in heat exchanger(kg/m^3)	2.68	12.71	43.63	110.65	96.6	35.67	10.42	3.35
Heat exchanger water flow rate (kg/s)	0.2667	0.25	0.25	0.175	1.0041	1.2986	1.2986	1.2986
Air flow of heat exchanger (kg/s)	15.9				29.4167			
volume of gas tank(m^3)	5225							
Surface area of gas tank(m^2)	6500							
Running time(min)	480				78			
Pressure during the release phase(kPa)	7							

CONCLUDING REMARKS

China is trying to ease the pressure of environmental pollution and energy shortages by using clean electricity. Energy structure is transitioning to a more scientific energy mix in which clean energy will play a vital role. The role of solar and wind energy is becoming increasingly significant. Currently, the curtailment problem is considered the main obstacle that obstructs the adoption of renewable energy technologies in China. The country's domestic demand has lagged behind its expanded manufacturing capacity, which leads to a waste of energy. Therefore, we should not neglect the fact that the transition of energy structure is a long-term process.

This study reviews the situation and obstacles to the development of renewable energy in China. According to diverse methods of stabilizing output power, two modes are summarized, i.e., multi-energy resources complementary modes (based on natural or manual adjustment) and energy storage model.

It is suggested that a combination of complementary mode and energy storage device is appropriate for large-scale renewable energy projects. The specific production pattern and capacity need to be finalized according to local conditions, such as weather, wind and PV curtailment characteristics, and load conditions. According to the overall energy deployment and the future trend of renewable energy utilization, the following suggestions are put forward:

(1) Up to now, China's clean energy is still at the quantity rather than quality stage. In the future, the proportion of clean energy in the total energy will steadily rise, and it will make more significant contributions to the environment, energy conservation, and emission reduction. In order to use clean energy more efficiently, the construction mode of the renewable energy industry should be changed from a mere quantity to an efficient use type, with the focus on balanced development between other energy sources.

(2) Hybrid energy storage project has excellent potential in the future. Based on the characteristics of different energy storage technologies, the different energy storage devices are suitable for the different power grids based on the grid size and characteristics of curtailment. Hybrid energy storage will be a viable option to make clean power available in more scenarios.

(3) Hydropower resources in Southwest China are vibrant. Therefore, it is a fresh idea that clean electricity is used to complement hydropower. However, the current management system will not dispatch power efficiently after the combination of hydropower and clean power. Therefore, it is urgent to change the management plan according to the situation of coordinated power generation to achieve the total consumption of local energy resources.

ACKNOWLEDGMENT

The authors would like to acknowledge the support received from the Royal Academy of Engineering under the UK-China Industry-Academia Partnership Programme scheme (UK-CIAPP\201) for this research project.

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