

Key Factors for Efficient Consumption of Renewable Energy in a Provincial Power Grid in Southern China

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Abstract—The development of renewable energy sources (RES) is important to promote the energy transition and address climate change. Unlike the centralized RES power plants in the north of China, the distributed RES power plants in the south of China for achieving local consumption have become an effective alternative. However, the differences between RES and hydropower consumption have become obvious in some areas. This paper investigates the key factors affecting the abandonment of RES in the south of China. To alleviate the problem of RES consumption, various measures are discussed from the aspects of evaluating the consumption capacity of power grids at different voltage levels, optimizing demand-side management, flexibly for reforming the peak-shaving power sources of thermal power plants and strengthening inter-provincial transactions. The production simulation is used to validate the analysis and discussion.

Index Terms—Hydropower, power consumption, renewable energy, wind power.

I. INTRODUCTION

WITH the reduction of fossil energy resources and the increasing concerns about global environmental issues, such as climate change, a worldwide agreement has evolved to promote sustainable energy by developing new renewable energy technology [1]. As a major energy-consuming country, China has developed and utilized large-scale renewable energy sources (RES) to ensure a stable energy supply, adjust and optimize energy structures, protect the ecological environment, reduce greenhouse gas emissions, and drive economic transformation and industrial upgrading [2]–[5].

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In northern China, the renewable energy resources are abundant and easy to be developed and utilized. However, wind power and photovoltaic curtailment is a serious problem because of the small local loads [6]–[9], limited transmission capacity and electricity trading. To this end, the National Development and Reform Commission in the “Strategic Action Plan for Energy Development (2014–2020)” clearly encouraged the development of distributed RES in southern China [10]. In the past five years, the average annual growth rate of RES in Southern China has exceeded 150%, and was over 200% in some provinces and regions.

In the southern region, the renewable energy resources are relatively poor. However, distributed RES is easy to be consumed because RESs are often near the load centers [10]–[13]. What’s more, some transaction sections in the south of China are narrow and RES is strongly coupled with small hydropower, thermal power and other types of power plants [14]. The phenomenon of hydropower and wind power curtailment during the flood season is difficult to eliminate [15], [16].

Based on the analysis of the basic situation related to the operation and planning of RES in southern China, this paper systematically elaborates on the current situation of RES consumption in southern China. The key factors affecting RES consumption are analyzed, and the measures and methods to solve these problems are proposed.

II. CURRENT SITUATION OF RES CONSUMPTION IN THE SOUTH OF CHINA

With the rapid growth of RES, the phenomenon of wind power and photovoltaic curtailment becomes more prominent than ever before [17], [18]. According to a documentary titled “National Monitoring and Evaluation Report on the Development of Renewable Energy and Electricity in 2015,” which was published by the National Energy Administration of China, the total amount of wind power and photovoltaic curtailment in 2015 was about 38.8 billion kilowatt-hours, of which 33.9 billion kilowatt-hours is wind power curtailment and 4.9 billion kWh is photovoltaic curtailment [19], [20]. It is worth noting that in Yunnan Province, which is rich in hydropower resources, wind power curtailment has reached 300 million kWh in 2015. In order to ensure the priority of wind power consumption, a 15 billion kilowatt-hours hydropower was abandoned in the same period. In 2016, similar to Yunnan

Province, the wind power generation capacity of Hunan power grid was 1.76 billion kWh, and the abandoned wind power was 105 million kWh, of which the proportion of abandoned wind in the power transmission channel and in peak regulation was 1:9. Abandoned hydropower has exceeded 900 million kWh as the result of wind power consumption. According to the relevant data released by China's National Bureau of Statistics, in 2017, the province with the highest proportion of renewable energy is Sichuan, where the proportion has reached 82.9%, and the lowest in Fujian Province which was only 30.0% [21]. The local provincial power grid is under great pressure.

At the same time, in the remote areas of the southern provinces, such as the western mountainous areas with abundant hydropower and wind power resources in Hunan Province, during the flood season, the competition for transmission channels between hydropower and wind power may be caused by several factors: relative weakness of power grid channels, the decrease of power consumption and the increase of peak-valley gaps. These factors may result in a severe RES consumption problem in some areas, which is primarily manifested as the transmission conflict between the wind power in mountains and the smaller hydropower. The installation and proportion of renewable energy in typical southern provinces are shown in Table I [1].

TABLE I
RENEWABLE ENERGY INSTALLED CAPACITY AND RATIO IN TYPICAL PROVINCES OF SOUTHERN CHINA IN 2017

Name	Hubei	Hunan	Guangxi	Sichuan	Guizhou	Yunnan
Total	71.24	42.77	43.37	97.21	58.03	89.05
Hydroelectric power	36.71	15.70	16.65	77.14	21.19	61.86
Wind power	2.53	2.63	1.50	2.10	3.69	8.19
PV	4.13	1.76	0.69	1.35	1.55	2.33
Renewable energy	43.37	20.09	18.84	80.59	26.43	72.38
Renewable energy ratio	60.9%	47.0%	43.4%	82.9%	45.5%	81.3%

Note: The unit is GW.

III. ANALYSIS OF KEY FACTORS AFFECTING RES CONSUMPTION IN SOUTHERN CHINA

A. Analysis of Key Factors

1) The Relationship Between Load Level and RES Distribution

In the remote mountainous areas of southern China, where the demand for electricity is relatively low, the distribution of RES and load demand are reversed from the perspective of geographical position. Taking Hunan Province as an example, the proportion of load in the western region of Hunan Province is only 35%, but 60% of the RES installation is situated in this area. The penetration of RES in Chenzhou, Shaoyang, Yongzho, and Huaihua Provinces has exceeded 40%. If small hydropower plants with the characteristic of uncertainty are further considered, the penetration of RES would be over 80% [22]. Due to the limitation of local load scale, higher regulation performance of power sources and power grids are required for RES consumption.

2) Peak Shaving Ability of Power Sources

The power supply in most of southern China primarily relies

on hydropower and thermal power is only a supplemented source. The overall regulation performance of the power sources is weak. Taking Hunan Province as an example, by the end of 2017, there were only four hydropower stations with multi-year regulation capacity, i.e., Sanbanxi, Dadongjiang, Baiyun and Jutianhe. The total capacity of these stations was only 1.754 GW [22]. There is only one pumped-storage power station (Heilufeng station) with a capacity of 1.2 GW. In general, the proportion of small hydropower is larger in remote mountainous areas with abundant RES. Most of the hydropower stations are run-of-river types, which do not have the capability of peak shaving. At the same time, the flexibility renovation of the main large-scale thermal power station is limited by many factors such as capital, technology limitations, etc., with 50% of the total capacity being used to provide peak shaving service.

3) Power Consumption Characteristics of RES and Small Hydropower

Wind farms in Hunan Province are primarily distributed in mountainous areas and integrated into the main grid in a distributed manner. These wind farms are located in the areas where hydropower stations are centralized. Due to the intermittent consumption characteristics, the power output of wind farms in mountainous areas with small hydropower is seriously overlapped in the flood season, which often leads to greater pressure on power consumption in the power grid.

4) Conductor Section Selection of RES Transmission Lines

China's Renewable Energy Law explicitly requires power grid enterprises to undertake the construction of RES transmission projects. Most of the wind farms in the southern mountainous areas are built at an altitude of 800 meters. The ridge length of wind resources is more than 10 kilometers, which results in a risk of large-scale icing in winter. The unit cost is 30%–50% higher than that in the plains. Therefore, the unit scale investment is generally larger. At present, the planning and design units still use the economic current density index searching method, which was published in 1955 for selecting the conductor section of RES transmission lines. This method is greatly influenced by the material cost, electricity price, and other parameters, but does not take the intermittent power output of RES into consideration, which results in deviation in decision-making and waste of investment and operations. Moreover, the mountain resource planning involves high uncertainty due to the rapid updating of the technology of wind generators in mountainous areas, which increases the difficulty of conductor section selection of RES transmission lines.

5) The Influence of External Power Transmission Curve

The main energy in China is primarily distributed in the western areas. Hence long-distance transmission is necessary for power transmitting to the southern load center. According to the level of the regional electricity shortage, the scale of the power transmission can be determined. However, the power transmission curve is often uncertain. It has a greater correlation with the power supply structure at the sending end, and also affects the level of RES consumption in the receiving provinces.

B. Case Study of Typical Provincial Power Grid

Hunan Province, which is a typical province in southern China, is selected as a typical scenario for analysis. The calculation is as follows:

1) Load Level

The variation of load characteristics directly affects the peak shaving ability of wind farms, and the variation of the peak-valley difference index is the most important factor. From 2005 to 2015, the annual maximum daily peak-valley difference and the annual average peak-valley difference of the Hunan power grid showed an uptrend. The average annual growth rate of annual maximum peak-valley difference during the 11th Five-Year Plan period was 17.3%, the average annual growth rate (AAGR) during 2010–2015 was 16.2%, the AAGR during the 11th Five-Year Plan period was 14.4%, and the AAGR during 2010–2015 was 16.5% [22]. The results show that the annual maximum and the annual average value of the peak-valley difference of the Hunan power grid increased faster than the load growth rate in the recent ten year period, and the maximum daily peak-valley difference occurs in winter.

2020 is chosen as the research year. Three scenarios are considered here: the electricity consumption of the whole society is 222 billion kWh/216 billion kWh/208 billion kWh and the maximum load of the whole society is 46 million kWh/43.4 million kWh/39.6 million kWh, respectively. The abandonment rates are 7.39%, 7.77%, and 9.12% respectively [22].

2) The Scale of RES Installation

Wind power is the most difficult RES to be consumed in southern China. In the scenario of the Hunan power grid in 2020, the grid-connected capacity of photovoltaic and biomass power plants are 2 GW and 1.4 GW respectively. With the increase of the grid-connected capacity of wind farms from 1.5 GW to 7 GW, the wind power curtailment increased from 250 million kWh to 1.39 billion kWh. The growth speed of wind power curtailment is 18.6% faster than the grid-connected capacity of wind power. The corresponding curtailment rate shows a slight fluctuation, increasing from 8.3% to 10.3%.

At the same time, the integration of large-scale wind power will directly compress the usage of other RES. The cumulative photovoltaic power curtailment increases from 0.02 billion kWh to 0.4 billion kWh (curtailment rate will increase from 0.1% to 2.3%). The cumulative power curtailment of biomass power plants increases from 122 million kWh to 285 million kWh (power curtailment rate will increase from 1.8% to 4.4%). The total power curtailment of RES increases from 380 million kWh to 1.62 billion kWh, (curtailment rate will increase from 3.3% to 7.7%). From the above analysis, it can be seen that during the 13th Five-Year Plan period, the large-scale integration of wind power in Hunan Province will inevitably lead to partial wind curtailment. When the grid-connected capacity of wind power is about 1.5 MW to 7 MW, the conservatively estimated wind curtailment rate is about 8.3%–10.1%.

3) The External Power Transmission Curve

Five typical operational curves of the JiuHu HVDC project, which is proposed in the report of “Research on Wind Power Transmission and Consumption Schemes in Gansu Province” by Beijing Economic and Technological Research Institute of the State Grid and China Electric Power Research Institute, are shown in Fig. 1. The simulations of the operation of the Hunan power grid in 2020 are performed based on different operational curves of the JiuHu HVDC project. The results show that: 1) the utilization hours of the operational curve schemes 2, 4 and 5 of the JiuHu HVDC project are more than 7,000 hours, which seriously squeezes the power generation in Hunan Province. On the premise of ensuring the economic operation of the Hunan thermal power, these three schemes are obviously unreasonable; 2) For the operational curve schemes 3, 4 and 5 of the JiuHu HVDC project, the Jiuquan station transmits small electrical power in large loads and in dry season mode. Whereas the Jiuquan station transmits large-scale power in small load and dry season mode. These three schemes increase the peak-shaving pressure of the Hunan power grid, or more RES power generation is forced to be abandoned; 3) the operational curve scheme 1 of the JiuHu HVDC project is relatively satisfying. During some part of high and low water periods (HWP and LWP), the Hunan power grid may be forced to provide peak-shaving for the integration of large-scale wind power in the Gansu power grid.

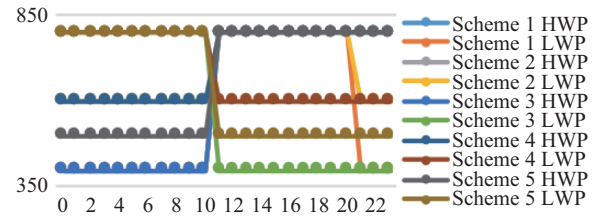


Fig. 1. Typical operational curves of the JiuHu HVDC project. The data comes from the “Research on Wind Power Transmission and Consumption Schemes in Gansu Province” published in 2013.

IV. SOLUTIONS

A. Evaluate the Consumption Capacity of the Southern China Power Grid

Distributed RES power plants in southern China are often located in the areas with relatively abundant water resources, low power demand, and are connected to a relatively weak power grid. Scientific and objective evaluation of the consumption capacity of the power grid is the key to improve the efficient utilization of RES. To evaluate the overall consumption capacity of RES during the planning period, the influences from the provincial power balance, power energy balance and the peak shaving balance should be taken into consideration. Based on the balance of the electric power in cities and counties with abundant RESs, the local absorption capacity can be evaluated, especially under the condition of a small load in the wet season; based on the principle of optimal total social investment in RES projects, the economic consumption capacity of a single RES project can be evaluated according

to the main-body investment, direct project investment and additional investment because of the power grid blockage and the project benefit indexes of resource differences. Based on the above three levels of consumption evaluation results, an evaluation system for the overall, local and economic consumption capacity of RES in southern China is established.

1) Balance of Electrical Power

Power balance is to ensure the static capacity margin of the power generation system, through the calculation and analysis of the power amount during the typical operational mode of the power system, to determine whether the power supply configuration scheme of the planned horizontal year system meets the power demand and energy demand of the system load. For the southern provincial power grid rich in hydropower and RES, because the effective power capacity of hydropower units change with water head and seasonal change of the flow, it is necessary to perform the monthly and yearly power balance calculation. With the increments of wind power and other RES, the volatility, and intermittent of the output power brings uncertainty to the system power balance, and thus scenario simulation needs to be set up for the southern region.

The power balance can be modeled in detail as follows. First, the power balance constraint of system subsections are expressed as,

$$\sum_{i \in s} P_{imt} + \sum_{i \in s} P_{Llmt} = L_{smt} \quad (1)$$

$$\sum_{s \neq 0} L_{smt} = L_{0mt} \quad (2)$$

where L_{smt} is the load power at t hour of the m^{th} month in the s^{th} level year; P_{imt} is the output power at t hour of the m^{th} month in the s^{th} level year; and P_{Llmt} is the power transmitted between sub regions at t hour of the m^{th} month in 1 level year (note that input is positive and output is negative).

Then, the energy balance constraint is introduced as,

$$\sum_{i \in s} E_{imt} + \sum_{l \in s} E_{Llmt} = E_{sm} \cap \sum_{s \neq 0} E_{sm} = E_{0m} \quad (3)$$

where E_{sm} is the predicted load consumed energy in the m^{th} month in the s^{th} level year; E_{imt} the generated energy by power generation station in the m^{th} month in the s^{th} level year; and E_{Llmt} is the energy transmitted into the system or subsystem by tie-lines in the m^{th} month in the s^{th} level year.

2) Balance of Peak Power Regulation

Peak load balancing is usually based on the priority sequence of generating units and the principle of optimization and coordination of generating load. The generating load is arranged according to the output curve of RES, and the peak load balancing of the system is achieved by the coordination and optimization of conventional power sources and ES equipment. In order to improve the RES consumption capacity of the power grid under the condition of large-scale and centralized access of RES.

However, for the provincial power grids rich in hydropower and RES in southern China, peak load regulation capacity in high or low water periods is often not enough to fully accept

the power generation output of RES with strong fluctuation and negative peak load regulation characteristics. Therefore, it is necessary to limit the power generation output of renewable energy through peak load regulation and power abandoning to ensure the balance of peak load regulation and the safe and stable operation of the system. Considering the influence of the undispatchability of power generation output from new energy sources such as wind power and photovoltaics on the safe and stable operation of the system, when there is insufficient peak load regulation, the power generation output of new energy power stations such as wind power and photovoltaic power stations should be first limited, then the power generation output of hydropower stations should be limited, and finally the power generation load operation of nuclear power stations should be considered.

The peak shaving balance constraints of the system and subsections can be expressed as,

$$\sum_{i \in s} \Delta P_{im} + \sum_{l \in s} \Delta P_{Llm} \geq \Delta L_{sm} + R_{Rsm} \quad (4)$$

where ΔP_{im} , ΔP_{Llm} are the peak regulating capacity of the i^{th} power station for all types of inter-partition lines (including tie lines and transmission lines) on a typical day of the m^{th} month in the horizontal year, respectively; ΔL_{sm} is the typical daily load peak-valley difference of the system for partition s in the m^{th} month of the level year.

B. Flexibly Update the Thermal Generator for Peak Regulating

The improvement of flexibility is expected to increase the peak shaving capacity of the thermoelectric unit by 20% of the rated capacity, with the minimum technical output reaching 40% to 50%. The peak shaving capacity of the pure condensing unit is increased by 15%–20% of the rated capacity, and the minimum technical output is up to 30%–35%. By strengthening the technical exchanges and cooperation with other countries, some power plants, which have the conditions for improvement, are expected to reach the international advanced level. The minimum technical output of the unit during stable combustion with no oil injection can reach to 20%–25%.

C. Strengthen Inter-provincial Power Trading

Taking the Hunan power grid as an example, the designed rated capacity of the Qi-Shao HVDC project cannot be consumed completely in Hunan at the current stage because of the load level and the weakness of the 500 kV power grid. The consumption of the Qi-Shao HVDC project in Hunan Province can be improved by strengthening the inter-provincial trade in central China and consuming the HVDC power in Hubei and Jiangxi Provinces.

D. Strengthen Demand Side Management

Through the formulation of policies such as peak-valley time-sharing electricity price, the demand side response mechanism is introduced to realize the participation of 5%–10% of the large industrial user load, to reduce the absolute value of the grid peak-valley difference, and to reduce the consumption pressure of renewable energy.

E. Accelerate the Construction of Pumped Storage

Considering that the construction cycle of pumped energy storage power station is relatively long (generally about 7 years), it is advisable to accelerate the preliminary work and the demonstration of supporting the grid-connection scheme, and introducing relevant policies to improve the peak shaving compensation mechanism.

V. PRODUCTION SIMULATION PRINCIPLE AND SIMULATION RESEARCH

Considering the big data of historical power generation output and aiming at different operational simulation objectives, this paper evaluates the overall and local consumption capacity of RES from three perspectives: power balance, electric quantity balance, and peak regulation. The scene characteristic indexes of RES are also employed for evaluation. SPER ProS 2015 was used to simulate power operations.

The aim of the optimal coordination between conventional power plants, energy storage equipment and RES generation is the lowest total power generation cost or the best effect of energy saving and emission reduction, which can be considered as a joint coordination optimization of multi-objective problems. Apart from considering all types of power station operational characteristics, the following factors are also taken into consideration: the planned maintenance and system load standby, the emergency power and load balance of each partition in the system, the annual output of all types of power station for hours and years, variable operating cost in fuel demand, abandoned water and electricity quantity of hydropower stations, and technical and economic indexes such as the exchange of power flow. The objective function can be expressed as,

$$\begin{aligned} \min F(P) = \min E_{WQ} \\ \cap \min\{E_{HQ} | \max(\bar{P}_{Hm} + R_{Hm}), m = 1, 2, \dots, 12\} \\ \cap \max\{\bar{P}_{Pm}(T_E, E_Q) + R_{Pm}(T_E, E_Q), m = 1, 2, \dots, 12\} \\ \cap \max\{P_{Am}(T_E) + R_{Am}(T_E), m = 1, 2, \dots, 12\} \\ \cap \max\{\min(\Delta P_{sm}(n_{Mm}), m = 1, 2, \dots, 12)\} \\ \cap \min\{F(P_T) | \max(\min(\Delta P_{sm}, m = 1, 2, \dots, 12)) \\ \cap \min(\Delta E_s)\} \end{aligned} \quad (5)$$

where, $\cap$ represents the apposition relation; $F(P)$ and $F(P_T)$ are the total annual cost of the thermal plant and power system; P and P_T are the output power of power stations and thermal power stations respectively; ΔE_s and ΔP_{sm} are the deficient and surplus power, respectively; n_{Mm} refers to the number of maintenance units arranged in a horizontal year in the m^{th} month; E_{WQ} and E_{HQ} are the power curtailment of RES and hydropower respectively. $E_Q = E_{WQ} + E_{HQ}$ is the sum of the wind power and hydropower curtailment of the horizontal annual power system; $\bar{P}_{Hm}$ and $\bar{P}_{pm}$ are the maximum power generation of the hydropower station and pumped storage power station in the m^{th} month of the horizontal year; P_{Am} is the output of the nuclear power plant in the m^{th} month of the horizontal year; R_{Hm} , R_{Pm} , and R_{Am} are the reserve capacities that are undertaken by hydropower, pumped storage

and nuclear power plants at the level of the m^{th} month of the horizontal year, respectively. T_E is the expected operating hours of the plant.

Considering the optimization and coordination between conventional power sources and energy storage equipment and RES generation, the balance constraints of the system and district power supply and power station operational constraints are primarily taken into account. And considering the zoning constraints on the power balances among them, the system generally includes power balance, load and emergency constraints, load balance, the maximum transmission line capacity constraints and power balance constraints, security constraints, lower thermal power spinning reserve capacity, water and electricity, pumped storage power plant spare capacity limit constraint, thermal power unit overhaul capacity constraint and the constraint of energy conservation and emissions reduction, etc.; The operational constraints of a power station generally include upper and lower limits of power generation output, energy consumption, lower limits of power consumption, maintenance site constraints, power balance constraints of a hydropower station, daily power balance constraints of a pumped storage power station, constraints on the number of daily startups of a thermal power station, constraints on the minimum startup and shutdown of a thermal power station during peak regulating operation, etc. The following are some of the major constraints listed. (Peak load regulation constraint of electric power was added previously).

1) Constraint on the maximum transmission capacity of lines between subsections is,

$$C_{L-lm} \leq P_{Llmt} + R_{LRlm} + R_{LSlm} \leq C_{L+lm} \quad (6)$$

where C_{L+lm} , C_{L-lm} are the maximum forward and reverse transmission capacity of all types of zonal lines (including tie lines and transmission lines) in the m^{th} month of l horizontal year, respectively.

2) Constraint on System and partition thermal power rotating reserve is expressed as,

$$\sum_{i \in s} R_{T Rim} \geq R_{Ts \min} R_{Rsm} \quad (7)$$

where $R_{T Rim}$ is the thermal reserve capacity for thermal power stations in the m^{th} month of l horizontal year; $R_{Ts \min}$ is the minimum proportion of system or sub- s rotating reserve for thermal power units.

3) The upper limit of reserve capacity of the system and zoned hydropower and pumped storage power stations is,

$$\sum_{i \in s} R_{Him} + \sum_{i \in s} R_{Pim} \leq R_{Hs \max} (R_{Rsm} + R_{Ssm}) \quad (8)$$

where R_{Him} , R_{Pim} are the reserve capacity of the system undertaken in year m and district s of hydropower and pumped storage power stations, respectively; $R_{Hs \max}$ is the maximum proportion of the total reserve of the system or zone for the system or zone s hydropower and pumped storage power station.

4) Constraint of system and zone thermal power unit maintenance capacity:

$$R_{Ms \min} C_{Ts} \leq \sum_{i \in s} n_{T M i m} C_i \leq R_{Ms \max} C_{Ts} \quad (9)$$

where $R_{Ms \max}$, $R_{Ms \min}$ are upper and lower limits of the thermal power maintenance capability of the system or partition s , respectively; CT_s is the total thermal power installed capacity of the system or zone s ; and n_{TMim} is the number of maintenance units per year and month for level I of thermal power station.

5) Constraint of the plant maintenance site is defined as,

$$n_{Mim} \leq \bar{n}_{Mi} \quad (10)$$

where $\bar{n}_{Mi}$ and n_{Mim} are the number of maintenance units and the actual number of maintenance units in m months are arranged for power station i at the same time, respectively.

6) Power balance constraint of hydropower station is defined as:

$$\sum_{t=1}^{24 \times D_m} (P_{Himt} + P_{Qimt}) = 24D_m P_{HAVim} \quad (11)$$

where P_{HAVim} , P_{Himt} , and P_{Qimt} are the average annual m -month output, t -hour power generation output and peak-regulating and water-abandoning power of the hydropower station i level, respectively; D_m is the number of days in the m^{th} month.

7) Balance constraint of the daily electric quantity of the pumped storage power station is expressed as,

$$\sum_{t=1}^{24} P_{Pimt} = \eta_i \sum_{t=1}^{24} L_{Pimt} \quad (12)$$

$$E_{PVim} = \sum_{t=1}^{24} P_{Pimt} \leq E_{PVi} \quad (13)$$

where E_{PVi} and η_i are the maximum pumping capacity of pumped storage power station i and the pumping-power generation conversion efficiency, respectively; E_{PVim} , P_{Pimt} and L_{Pimt} are the pumped storage power station i level year m th month typical day pumping electricity, typical day t -hour power generation output and pumping load, respectively.

8) Constraint of the shortest startup and shutdown time when the thermal power station starts, stops and operates with peak regulation is expressed as,

$$t_{Rim} \geq t_{Ri} \cap t_{Sim} \geq t_{Si} \quad (14)$$

where t_{Rim} , t_{Sim} are respectively the number of hours of continuous startup and hours of continuous shutdown when the thermal power station starts and stops on a typical day of peak regulating operation in the m^{th} month of the i^{th} level year; t_{Ri} and t_{Si} are the lower limits of continuous startup hours and continuous shutdown hours when the thermal power station i starts to stop and regulates peak operations, respectively.

For the optimization and coordination among conventional power supplies, energy storage equipment, and RES generation, the system and regional power balance constraints and power station operational constraints should be taken into account.

This is according to the power demand forecast of the Hunan grid, power supply approval and planning. It is predicted that in 2025, 2030 and 2035, the consumed power can achieve 242.9 billion kWh, 290 billion kWh and 350 billion kWh,

respectively. The total social load power will achieve 52.4 million kW, 65 million kW and 77 million kW, respectively. The total installed power supply will be 61.3 million kW, 65.73 million kW and 68.38 million kW, respectively. The power transmitted from other regions is 21.03 million kW, 30.63 million kW and 34.63 million kW, respectively. Other relevant parameters are shown in Tables II, III and IV.

TABLE II
INSTALLED CAPACITY OF POWER SOURCES DURING 2025–2035 IN HUNAN [23]

Year	Wind power	PV	Biomass energy	Thermal energy	Hydroelectric power	Total
2025	9	5	1.30	26.46	19.54	61.30
3030	12	7	1.80	25.14	19.79	65.73
2035	14	9	2.20	29.14	20.04	68.38

Note: The unit is GW.

TABLE III
LOAD OF BASIC SCENARIOS DURING 2025–2035 IN HUNAN [23]

Year	Total consumption ($\times 10^2$ GWh)	Load power ($\times 10$ MW)
2025	2429	5240
3030	2900	6500
2035	3500	7700

TABLE IV
OUT-OF-REGION INPUT POWER DURING 2025–2035 IN HUNAN [23] (BASIC SCENARIOS)

Transmission line	Destination	2025	2030	2035
Qi-Shao DC line	Eastern Hunan	7.44	7.44	7.44
E-Xiang line	Northwest Hunan	2.40	2.40	2.40
Changsha UHVAC	Eastern Hunan	3.75	3.75	3.75
Xiangnan DC line	Southern Hunan	7.44	7.44	7.44
Xiangdong DC line	Eastern Hunan	–	9.60	9.60
Xiangnan AC line	Southern Hunan	–	–	4.00

Note: The unit is GW.

The simulation results show that without taking relevant measures, the wind curtailment rates in 2025, 2030 and 2035 are 4.0%, 13.8% and 8.9%, respectively. The PV curtailment rates are 2.3%, 8.6% and 1.2%, respectively. The total amount of RES and hydropower curtailments are 9.2, 41.7 and 2.78 billion kWh, respectively.

In the basic scenario, the proposed RES consumption measures are illustrated in Table V.

Table V indicates that: 1) The peak-shaving capacity of thermal power units will increase by 20%. In 2025, 2030 and 2035, the Hunan power grid will increase the consumption of RES by 120 million kWh, 540 million kWh and 360 million kWh, respectively and the curtailment rate of wind and photovoltaic will decrease by 0.5%–1.7% and 0.1%–0.7%, respectively. The pumped storage capacity will be increased by 0.51 million kW, 1.2 million kW and 1.4 million kW, respectively which could promote the RES consumption of 140 million kWh, 67 million kWh and 470 million kWh, respectively. The wind curtailment rate will be decreased by 0.8%–2.4%, with the PV curtailment rate decreased by 0.2%–1.2%.

2) Through cross-regional power trading, the Hunan power grid will increase the consumption of RES by 170 million kWh, 770 million kWh and 510 million kWh in 2025, 2030

TABLE V
RESULTS OF THE MEASUREMENTS FOR RENEWABLE ENERGY CONSUMPTION DURING 2025–2035 IN HUNAN [23]

Scenarios	Renewable energy curtailment			Rate of wind curtailment			Rate of PV curtailment		
	2025	2030	2035	2025	2030	2035	2025	2030	2035
Basic	920	4170	2780	4.00%	13.80%	8.90%	2.30%	8.60%	1.20%
Reform of thermal units	800	3630	2420	3.50%	12.10%	7.80%	2.10%	7.90%	1.10%
Pumped storage	780	3500	2310	3.20%	11.40%	7.10%	2.00%	7.40%	1.00%
Electricity trading	750	3400	2270	2.90%	10.00%	6.50%	1.70%	6.40%	0.90%
Demand response	640	2900	1930	2.40%	8.30%	5.30%	1.50%	5.60%	0.80%

Note: The unit is GWh.

and 2035, respectively. The wind curtailment rate will decrease by 1.1%–3.8%, with the PV curtailment rate decreased by 0.3%–2.2%.

3) Through the demand side response, the Hunan power grid will increase the consumption of RES by 280 million kWh, 1.27 billion kWh and 850 million kWh in 2025, 2030 and 2035, respectively. The wind curtailment rate will decrease by 1.6%–5.5%, with the PV curtailment rate decreased by 0.4%–3.0%.

4) The results shown in Fig. 5 are obtained using the four measures separately in the basic situations. Taking the comparison between the demand side response and pumped storage as an example, the demand side response directly optimizes the load curves, and increases the power demand during the off-peak period. In comparison, the effects of the pumped storage are mediocre due to the limits of installed capacity and pumping-generation efficiency (it is generally 75%, which means four-hour pumping and three-hour generation).

The simulation results above reflect the implementation effect and effectiveness of individual measures. With the influence from the input power of the neighboring utility grid on the Hunan power grid in 2030 and 2035, the consumption of RES will be more difficult. If the measures above can be used, the comprehensive simulation results show that RES curtailment could be limited to 920 million kWh and 590 million kWh, with wind curtailment rates decreasing to 3.0% and 1.9%, PV curtailment rate decreasing to 1.9% and 0.3%, which can meet the requirements of less wind and PV curtailment issued by the energy bureau, and reach the expected high-efficiency level.

VI. CONCLUSION

The distributed RES stations in southern China are quite different from the centralized RES stations in northern China, and have become an effective way to obtain efficient use of dispersed wind and PV resources. Influenced by several factors such as the distribution relationship between load and the RES in southern China, the peak-shaving capacity of power generation, the consumption characteristics of RES and small hydropowers, the safety and economic selection of transmission lines, and the out-of-area power curves, the RES in southern China may suffer a large number of wind curtailment possibilities in the next decade.

Therefore, several methods are put forward, such as scientific evaluation of consumption capacity of power grids at all voltage levels, strengthening demand side management, flexible improvement of thermal power for peak-shaving, strengthening of inter-provincial trade and promoting consumption of out-of-area input power. Simulation of RES consumption

measures shows that the above measurements can effectively limit the wind curtailment rate of RES, which is of great significance for scientific development and consumption of RES in southern China.

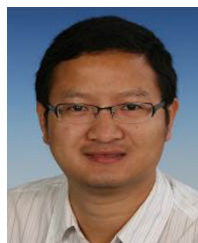
REFERENCES

- [1] National 13th Five-Year Energy Planning. *National Development and Reform Commission*. 2016.
- [2] J. Xu, B. Wang, Y. Z. Sun, Q. Xu, J. Liu, H. Q. Cao, H. Y. Jiang, R. B. Lei, and M. J. Shen, "A day-ahead economic dispatch method considering extreme scenarios based on wind power uncertainty," *CSEE Journal of Power and Energy Systems*, vol. 5, no. 2, pp. 224–233, Jun. 2019.
- [3] M. Javadi, A. M. Malyscheff, D. Wu, C. Q. Kang, and J. N. Jiang, "An algorithm for practical power curve estimation of wind turbines," *CSEE Journal of Power and Energy Systems*, vol. 4, no. 1, pp. 93–102, Mar. 2018.
- [4] C. Chen, W. J. Du, H. F. Wang and T. Littler, "Sub-synchronous oscillations in power systems caused by grid-connected wind farms—A survey of mechanism studies," *CSEE Journal of Power and Energy Systems*, vol. 4, no. 4, pp. 495–503, Dec. 2018.
- [5] Y. S. Xue, X. Lei, F. Xue, C. Yu, Z. Y. Dong, F. S. Wen, and P. Ju, "A review on impacts of wind power uncertainties on power systems," *Proceedings of the CSEE*, vol. 34, no. 29, pp. 5029–5040, Oct. 2014.
- [6] G. Mu, Y. Cui, and G. G. Yan, "A static optimization method to determine integrated power transmission capacity of clustering wind farms," *Proceedings of the CSEE*, vol. 31, no. 1, pp. 15–19, Jan. 2011.
- [7] J. Z. Liu, D. L. Zeng, L. Tian, M. M. Gao, W. Wang, Y. G. Niu, and F. Fang, "Control strategy for operating flexibility of coal-fired power plants in alternate electrical power systems," *Proceedings of the CSEE*, vol. 35, no. 21, pp. 5385–5394, Nov. 2015.
- [8] Y. X. Yu, J. R. Wang, and X. Y. Lv, "Security value based expansion planning of power system with integration of large-scale wind power," *Science China Technological Sciences*, vol. 55, no. 7, pp. 1908–1922, May 2012.
- [9] X. F. Wang, X. H. Wei, L. H. Ning, and X. L. Wang, "Integration techniques and transmission schemes for off-shore wind farms," *Proceedings of the CSEE*, vol. 34, no. 31, pp. 5459–5466, Nov. 2014.
- [10] X. M. Yuan, S. J. Cheng, and J. Y. Wen, "Prospects analysis of energy storage application in grid integration of large-scale wind power," *Automation of Electric Power Systems*, vol. 37, no. 1, pp. 14–18, Jan. 2013.
- [11] D. Xiang, Z. C. Hu, Y. H. Song, and H. J. Ding, "Business model and day-ahead dispatch strategy to reduce wind power curtailment through vehicle-to-grid," *Proceedings of the CSEE*, vol. 35, no. 24, pp. 6293–6303, Feb. 2015.
- [12] C. Dong, M. J. Li, G. F. Fan, Y. H. Huang, and X. F. Li, "Research and application of renewable energy accommodation capability evaluation based on time series production simulation," *Electric Power*, vol. 48, no. 12, pp. 166–172, Dec. 2015.
- [13] D. W. Liu, J. B. Guo, Y. H. Huang, and W. S. Wang, "Dynamic economic dispatch of wind integrated power system based on wind power probabilistic forecasting and operation risk constraints," *Proceedings of the CSEE*, vol. 33, no. 16, pp. 9–15, Jun. 2013.
- [14] Y. Li, Y. Zou, Y. Tan, Y. J. Cao, X. D. Liu, M. Shahidehpour, S. M. Tian, and F. P. Bu, "Optimal stochastic operation of integrated low-carbon electric power, natural gas, and heat delivery system," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 1, pp. 273–283, Jan. 2018.
- [15] F. Liu, N. Li, X. C. Zhang, and S. B. Wang, "Research on optimal matching scheme of renewable energy based on renewable energy consumption ability," in *Proceedings of the 2nd IEEE Conference on Energy Internet and Energy System Integration*, 2018.

- [16] J. W. Zhou, D. Liu, Q. S. Li, and J. Nong, "Comparison of renewable energy consumption modes in active distribution network," in *International Conference on Renewable Power Generation*, 2016.
- [17] Y. C. Zhang, R. Yang, K. Q. Zhang, H. G. Jiang, and J. J. Zhang, "Consumption behavior analytics-aided energy forecasting and dispatch," *IEEE Intelligent Systems*, vol. 32, no. 4, pp. 59–63, Aug. 2017.
- [18] M. Li, H. Nishiyama, N. Kato, Y. Owada, and K. Hamaguchi, "On the energy-efficient of throughput-based scheme using renewable energy for wireless mesh networks in disaster area," *IEEE Transactions on Emerging Topics in Computing*, vol. 3, no. 3, pp. 420–431, Sep. 2015.
- [19] O. Arnold, F. Richter, G. Fettweis, and O. Blume, "Power consumption modeling of different base station types in heterogeneous cellular networks," in *2010 Future Network & Mobile Summit*, 2010, pp. 1–8.
- [20] L. Bai, Z. Chen, and J. R. Chu, "Research on energy consumption for heating from implementing "50% Energy-saving Standard" and "65% Energy-saving Standard"," *Advanced Materials Research*, vol. 608–609, pp. 1246–1251, Dec. 2012.
- [21] China renewable energy development report 2017, *National Bureau of Statistics*, 2017.
- [22] Hunan "13th five-year" power grid planning report, *State Grid Hunan Company*, 2017.
- [23] Hunan "14th five-year" power grid planning report, *State Grid Hunan Company*, 2019.



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