Study on the Economic Optimization of Energy Storage System Configuration for Wind Power Accommodation in Guangdong Province

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Abstract. Based on the wind power development plan of Guangdong, wind power accommodation capacity of Guangdong power grid is calculated with peak regulation constraints. The sensitivity and adjustability of four parameters that affect wind power accommodation capacity were compared. Taking the minimum life cycle annual cost as objective function, the problem of energy storage system configuration is solved by enumeration method. The results show that: there will be a surplus of wind power during valley load period with peak regulation constraints in 2030, and the difference from actual installed capacity is 17.29 GW; the minimum output coefficient is the best adjustment parameter among the four parameters; according to the comparison of seven schemes; the fifth scheme has the best economic performance with the life cycle annual cost of 13.53 billion yuan and the efficiency of 63.62%. The power ratio of compressed-air energy storage (CAES), battery storage (BS) and super capacitor energy storage (SCES) is 85.40%, 8.63%, 5.97%, and the capacity ratio is 98.39%, 1.61%, 3.8e-6%, respectively.

1. Introduction

According to the development plan of offshore and onshore wind power of Guangdong, the total installed capacity will achieve 40 GW by 2030 [1, 2]. The phenomenon of wind power curtailment was serious in China in 2018, which was about 4.4% of the consumption amount of the non-hydro renewable energy [3, 4]. Because of the characteristics of wind power output, there will be two situations in Guangdong in the future. One is positive peak regulation (figure 1a), wind power output is synchronized with load so that the wind power can be fully accommodated. The other is anti-peak regulation (figure 1b), wind power output is opposite to load, which may lead to wind power curtailment due to the difficulty of peak regulation. In this case, energy storage system needs improving the wind power accommodation capacity of power grid.
The problem of anti-peak regulation is solved by the connection to Nordic Power Systems and the use of gas generator units in Denmark, and by the combination of wind power and other flexible power supplies in Germany, but there is no unified solution in China [5]. Researches include the combined heating mode, the cooperation with energy storage and so on in this area. Ge [6] proposed a coordinated operation control strategy based on combined heating mode of electric and coal boiler for the wind power curtailment in three north areas of China, and the simulation result shown that the wind power accommodation capacity during valley load period could be improved effectively. Luo [7] studied the relationship between wind power accommodation capacity and the demand for the flexibility of thermal power units, it is found that only thermal power units involved in peak regulation could not accommodate all wind power in the future peak regulation demand by take calculation in the northern Hebei Province of China. Miranda [8] put forward a battery energy storage system fit for island, and verified that the wind power accommodation capacity and the flexibility of island power system can be improved by an example. The problem of energy storage system configuration is required to solve when it is used to solve the problem of anti-peak regulation. Chen [9] proposed a strategy of combined operating of tower drum elevator and energy storage system to solve the wind curtailment and the configuration problem was solved by gen etic algorithm. Guo [10] used particle swarm optimization to solve the problem of the hybrid energy storage configuration based on the net power frequency decomposition compensation strategy. Adaptive genetic algorithm was adopted by Xia [11] to calculate the best hybrid energy storage system configuration scheme in multi-energy complementary microgrid. There is no research on anti-peak regulation that cause by wind power and the energy storage system configuration for wind power accommodation in the future in Guangdong Province.

Three tasks are carried out in this paper in order to study whether the energy storage system is needed for Guangdong power grid to improve wind power accommodation capacity and how to do energy storage system configuration can maximize its economic performance. Firstly, the wind power accommodation capacity is calculated with peak regulation constraints. Then the best measure to improve the wind power accommodation capacity is discussed through sensitivity analysis. Finally, the enumeration method is used to solve the energy storage system configuration problem by taking the minimum life cycle annual cost as the objective function, and the construction of energy storage system in the future is discussed.

2. Study Method

2.1. Wind Power Accommodation Capacity Calculation Model with Peak Regulation Constraints

With the load sample, there are unitary linear, semi-log and exponential sample regression models,

\[ \hat{P} = \hat{a} + \hat{b}x \] (1)
\[ \hat{P} = \hat{a} + \hat{b} \ln x \]  

(2)

\[ \hat{P} = \hat{a} \exp(\hat{b}x) \]  

(3)

where \( x \) is the year, \( \hat{P} \) is the predicted value of annual peak load, \( \hat{a} \) and \( \hat{b} \) are sample regression parameters.

By mathematical transformation, equations (2) and (3) can be transformed into a linear model like equation (1). The sample regression parameters can be calculated from

\[
\begin{align*}
\hat{b} &= \left( n \sum_{j=1}^{n} x_j P_j - \sum_{j=1}^{n} x_j \sum_{j=1}^{n} P_j \right) \left[ n \sum_{j=1}^{n} x_j^2 - \left( \sum_{j=1}^{n} x_j \right)^2 \right]^{-1} \\
\hat{a} &= \left( \sum_{j=1}^{n} P_j - \hat{b} \sum_{j=1}^{n} x_j \right) n^{-1}
\end{align*}
\]

(4)

where \( n \) is the number of samples, \( j = 1, 2, 3, \ldots, n \), \( x_j \) is the year of the \( j \)th pair in the sample, \( P_j \) is the corresponding peak load.

The coefficient of determination is needed to evaluate fitting degree of the models, which is defined as

\[
R^2 = \left[ \frac{\sum_{j=1}^{n} (P_j - \bar{P})^2}{\sum_{j=1}^{n} (\hat{P} - \bar{P})^2} \right]^{-1}
\]

(5)

where \( \bar{P} \) is the mean of loads in the sample [12].

The wind power accommodation capacity is the difference between load and the output of power supplies except wind power. The calculation is based on peak regulation constraints of power grid and considering the worst case that the wind power output is the highest while the load is the lowest. The annual valley load in Guangdong usually occurs in winter. The annual predicted peak load has been calculated so the daily peak load \( L_{\text{max}} \) and valley load \( L_{\text{min}} \) in winter can be obtained respectively by the annual peak-valley ratio and the daily minimum load ratio.

According to the power balance, the active power output of power supplies during peak load period can be calculated from

\[
P_{\text{Gmax}} = \frac{P_{\text{tie max}} - P_{\text{tie}} (1 - \sigma_{\text{los}})}{(1 - \sigma_{\text{los}})(1 - \sigma_{\text{in}})}
\]

(6)

where \( P_{\text{tie}} \) is the tie-line power, \( \sigma_{\text{los}} \) is the line loss rate, \( \sigma_{\text{in}} \) is the station service power consumption rate.

It is assumed that all pumped storage power stations are used to store energy during valley load period, the active power output of power supplies during valley load period can be calculated from

\[
P_{\text{Gmin}} = \frac{P_{\text{tie min}} - \mu P_{\text{tie}} (1 - \sigma_{\text{los}})}{(1 - \sigma_{\text{los}})(1 - \sigma_{\text{in}})} + P_{\text{pump}}
\]

(7)

where \( \mu \) is the coefficient of peak regulation to the tie-line power, \( P_{\text{pump}} \) is the installed capacity of pumped storage power stations.

The actual active power output of the units participating in peak regulation can be obtained by deducting the forced output from the active power output, the reserve capacity can be obtained from
the load reserve ratio and the active power output corresponding to the annual peak load. Then the maximum unit-operating capacity can be calculated from

$$P_{\text{cmax}} = P_{\text{fmax}} + P_{\text{re}}$$

(8)

where $P_{\text{fmax}}$ is the actual active power output of the units participating in peak regulation during peak load period, $P_{\text{re}}$ is the reserve capacity.

The least output of other power supplies can be calculated from

$$P_{\text{cmin}} = \varepsilon \cdot P_{\text{cmax}}$$

(9)

where $\varepsilon$ is the minimum output power coefficient.

The wind power accommodation capacity during valley load period is the difference between load and least output of other power supplies, so it can be calculated from

$$P_{\text{wind}} = \frac{P_{\text{fmin}} - P_{\text{cmin}}}{\xi}$$

(10)

where $P_{\text{fmin}}$ is the actual active power output of the units participating in peak regulation during valley load period, $\xi$ is the simultaneity factor of the wind power output.

2.2. Energy Storage System Configuration Method

The idea of energy storage system configuration is: firstly, objective function is determined, it is the minimum life cycle annual cost; secondly, the constraints are determined, including power, capacity and the charge-discharge constraints of energy storage system; finally, enumeration method is used to solve the problem of energy storage system configuration. There are two assumptions before that, one is that the energy storage stations only charge during valley load period; the other is that the energy stored by the energy storage system during valley load period can be completely released during the adjacent peak load period. When the wind power cannot be fully accommodated, load value at each time can be calculated according to the daily peak load, valley load and the curve of daily load per-unit value. Each load value is treated as valley load, so the corresponding wind power accommodation capacity can be calculated by the model in section 2.1. And then the part cannot be accommodated also can be obtained, which is called unbalanced power, the unbalanced power scatters are used to do curve fit.

2.2.1. Objective Function. The minimum life cycle annual cost is taken as the objective function due to the different lifetime of different types of energy storage. The whole lifetime is divided into three stages, including initial, middle and final stages. Because of the different efficiency, it is converted into the loss cost, so the life cycle annual cost can be calculated from

$$C_{\text{LCC}} = C_1 + C_{\text{OM}} + C_{\text{D}} + C_{\text{los}}$$

(11)

where $C_1$, $C_{\text{OM}}$, $C_{\text{D}}$ and $C_{\text{los}}$ are the annual cost of initial investment, middle operation and maintenance, final disposal and loss, respectively.

Initial investment cost of a type of energy storage can be calculated from

$$C_{\text{IZ}} = C_{\text{iz}}E_Z + C_{\text{pz}}P_Z$$

(12)

where $E_Z$ and $P_Z$ are the design capacity and power of this type of energy storage, respectively, $C_{\text{iz}}$ and $C_{\text{pz}}$ are the corresponding capacity and power unit cost, respectively.
Annual cost of operation and maintenance can be calculated from

\[ C_{\text{OM}} = \sum_{i=1}^{m} k_{\text{OMZ}} \frac{C_{\text{IZ}}}{T_Z} \]  

(13)

where \( m \) is the number of the types of energy storage, \( k_{\text{OMZ}} \) is the coefficient of operation and maintenance cost, \( T_Z \) is the life span of energy storage.

Annual cost of final disposal can be calculated from

\[ C_D = \sum_{i=1}^{m} k_{\text{DZ}} \frac{i}{(1+i)^{T_Z} - 1} \]  

(14)

where \( i \) is the discount rate, \( k_{\text{DZ}} \) is the coefficient of final disposal cost.

Annual cost of initial investment can be calculated from

\[ C_I = \sum_{i=1}^{m} C_{\text{IZ}} \frac{i(1+i)^{T_Z}}{(1+i)^{T_Z} - 1} \]  

(15)

Loss cost can be calculated from

\[ C_{\text{los}} = \sum_{i=1}^{d} \left( \int_{t_i}^{t_{i+1}} P \, dt \right) \left( 1 - \text{eff} \right) \times C_{\text{pv}} \]  

(16)

where \( P \) is the unbalanced power, \( t_i \) and \( t_{i+1} \) are the moment that the unbalanced power appeared and disappeared, \( \text{eff} \) is the efficiency of the energy storage system, \( C_{\text{pv}} \) is the price difference of peak and valley electricity, \( d \) is the days with loss cost.

2.2.2. Constraints. Power and capacity constraints are

\[ \begin{cases} 0 \leq P_{pc} \leq P_c \\ 0 \leq E_{pc} \leq E_d \end{cases} \]  

(17)

where \( P_c \) is the rated charging power, \( P_{pc} \) is the instantaneous charging power, \( E_{pc} \) is the remaining electric quantity of the power grid, \( E_d \) is the design capacity.

The charge-discharge constraint is

\[ \text{SOC}_{\text{min}} \leq \text{SOC} \leq \text{SOC}_{\text{max}} \]  

(18)

where \( \text{SOC} \) is state of charge.

2.2.3. Solution Method. The pumped storage power stations have been considered into the calculation in section 2.1, therefore, it is not involved in the energy storage system configuration again. Flywheel energy storage (FES) and super capacitor energy storage (SCES) are used as power-type storage to smooth power fluctuations, compressed-air energy storage (CAES) and battery storage (BS) are used as energy-type storage to store energy.

The design power of power-type storage system is the maximum unbalanced power before energy-type storage is turned on, so it is calculated from

\[ P_p = (1 + \theta) \eta_c \eta_{\text{inv}} (1 - \sigma_{\text{los}}) \max \left\{ P_{\mid \ell \in (t_i, t_{es})} \right\} \]  

(19)

where \( \theta \) is the margin, \( \eta_c \) is the efficiency of charge, \( \eta_{\text{inv}} \) is the efficiency of converter, \( t_{es} \) is the initial moment that the energy-type storage is turned on.
The design capacity of power-type storage system is the cumulative value of the unbalanced power before energy-type storage is turned on, it is calculated from

\[ E_p = (1 + \theta) \eta_e \eta_{inv} (1 - \sigma_{loss}) \int_{t_a}^{t_b} P dt (S_{Pinax} - S_{Pinin})^{-1} \]  

(20)

where \( S_{Pinax} \) and \( S_{Pinin} \) are the maximum and minimum value of state of charge of power-type storage.

The design power of energy-type storage system is the maximum unbalanced power, it is calculated from

\[ P_e = \eta_e \eta_{inv} (1 - \sigma_{loss}) \max \{ P [t] \in (t_e, t_f) \} \]  

(21)

The design capacity of energy-type storage system is the cumulative value of the unbalanced power after energy-type storage is turned on, it is calculated from

\[ E_p = \eta_e \eta_{inv} (1 - \sigma_{loss}) \int_{t_a}^{t_b} P dt (S_{Eminax} - S_{Eminin})^{-1} \]  

(22)

where \( S_{Eminax} \) and \( S_{Eminin} \) are the maximum and minimum value of state of charge of energy-type storage.

The enumeration method is used to solve the problem, and it can be divided into three steps. Firstly, the range of design power and capacity of power-type and energy-type storage system are calculated; then the range of design power and capacity of BS and SCES are calculated; finally, searching for a solution to achieve the objective function in the range. It is realized by the use of C++ program with the 5.10 version of Dev-C++.

The program flowchart is shown in figure 2, where \( P_{beamx}, P_{bminin} \) and \( P_b \) are the upper limit, lower limit and the value of the design power of BS, \( E_{beamx}, E_{bminin} \) and \( E_b \) are the upper limit, lower limit and the value of the design capacity of BS, \( X_{pb}, X_{eh} \) are the unit power and capacity. Same as before, subscript c, s and f are the represented of CAES, SCES and FES, respectively, \( C_{LCCmin} \) is the value of the minimum life cycle annual cost.

2.3. Parameter Setting

According to the collected annual peak load values from 2004 to 2018 and the gross domestic product (GDP) of Guangdong in the past years, curves drew in figure 3. The data of annual peak load values are from the official website of China Southern Power Grid and the data of GDP are from the official website of the National Bureau of Statistics of China.

The reasons for setting the values of boundary condition shown in table 1 are as follows: the annual maximum peak-valley ratio is usually around 51%-55%, so 55% is taken [13]; the annual average of the daily minimum load ratio was in the range of 64%-66% from 2010 to 2015 [14], 65% is taken in this paper; the historical data of line loss rate are from Ref. [15], use the equations (1)-(3) in section 2.1 to do curve fit and predicted by the one with the best fitting degree; the reserve capacity of Guangdong power grid is considered to be 5%-10% of the maximum power generation load, it is taken as 10% because of the importance of the electric network reliability; the minimum output power coefficient is related to the power supply structure, set as 0.4 [16]: the forced output consists only of nuclear power; the data of tie-line power in 2016 and 2020 are from Ref. [17] and the data in 2016 is replaced by it in 2015, the rest are predicted value; it is considered that the tie-line power could be reduced to half of the peak load during valley load period, so the coefficient of peak regulation to the tie-line power is 0.5; the simultaneity factor of the wind power output set as 0.65; the data of installed capacity of power supplies in 2016 and 2020 are respectively from Refs. [17, 18], the comprehensive development mode in Ref. [19] is adopted in 2030 and corrected by Refs. [1, 2], the data of 2025 is predicted by models in section 2.1; the station service power consumption rate is 8%.

The data of daily load per-unit value are obtained from figure 3 in Ref. [14] by the use of GetData Graph Digitizer (2.22 version).
The reasons for setting the parameters of energy storage system configuration shown in table 2 are as follows: the margin for the calculation of the design power and capacity of power-type storage system is 5%; the discount rate is 10%; the efficiency of converter is taken as 90%; the price difference of peak and valley electricity of general industrial and commercial power less than 1kV in Guangzhou (0.773375 yuan/kWh) is taken to calculate the loss cost; the data of electricity consumption from January 2013 to August 2018 are provided by related department; the electricity consumption trough of Guangzhou is January, February and December, which is considered to be the same as Guangdong; based on the mineral resources development in 2015 [22] and combined with the factors of the topography condition, the mining situation and so on, the number of CAES station that can be constructed is set as five; the design power of each one is 100 MW and it can be charged continuously for at least seven hours; the maximum capacity of SCES is limited to 10 MW for the reasons of environmental humidity requirements and construction scale.

![Figure 2. The flowchart of program.](image-url)

![Figure 3. Curves of GDP and annual peak load.](image-url)
### Table 1. Boundary conditions for the calculation of wind power accommodation capacity.

| Boundary condition | 2016 | 2020 | 2025 | 2030 |
|--------------------|------|------|------|------|
| Annual maximum peak-valley ratio (%) | 55   | 55   | 55   | 55   |
| Annual average of daily minimum load ratio (%) | 65   | 65   | 65   | 65   |
| Line loss rate (%) | 4.79 | 4.15 | 3.60 | 2.55 |
| Load reserve ratio (%) | 10   | 10   | 10   | 10   |
| Minimum output power coefficient | 0.4  | 0.4  | 0.4  | 0.4  |
| Force output | 9.38 | 16   | 23.49 | 31.14 |
| Tie-line power | 35   | 40   | 45   | 50   |
| Coefficient of peak regulation to the tie-line power | 0.5  | 0.5  | 0.5  | 0.5  |
| Simultaneity factor of the wind power output | 0.65 | 0.65 | 0.65 | 0.65 |
| Installed capacity of pumped storage (GW) | 5.69 | 7.28 | 8.48 | 9.68 |
| Installed capacity of wind power (GW) | 2.68 | 8    | 16.64 | 40   |

### Table 2. Parameters of energy storage.

| Parameter                  | BS       | CAES     | SCES     | FES      |
|----------------------------|----------|----------|----------|----------|
| Power cost (yuan/kW)       | 3000     | 6800     | 450      | 1800     |
| Capacity cost (yuan/kWh)   | 1800     | 1500     | 13000    | 20000    |
| Efficiency (%)             | 85       | 65       | 90       | 90       |
| Efficiency of charge (%)   | 90       | 80       | 95       | 95       |
| Coefficient of operation and maintenance cost | 0.12 | 0.01 | 0.01 | 0.01 |
| Coefficient of final disposal cost | 0.08 | 0      | 0.04    | 0        |
| Lifetime (year)            | 8        | 35       | 10       | 20       |
| Range of state of charge   | 0.05-0.95| 0.1-1   | 0.02-0.99 | 0.1-0.9 |
| Response time              | Hundred milliseconds | Minutes | Milliseconds | Ten milliseconds |

Note: The data are from Refs. [20, 21].

### 3. Results

#### 3.1. The Result of Wind Power Accommodation Capacity Calculation

The trend of curves of GDP and annual peak load are consistent, it shows an upward trend (figure 3). It is considered that the load increases with time, that is, there is a correlation between load and time. Therefore, regression analysis method in section 2.1 is adopted to predict load, and the results of 2020, 2025, 2030 are 124.22 GW, 153.19 GW, 182.08 GW, respectively. The model in section 2.1 is used to calculate the wind power accommodation capacity. The results are shown in table 3.

### Table 3. The calculation result of wind power accommodation capacity.

| Result                                      | 2016 | 2020 | 2025 | 2030 |
|---------------------------------------------|------|------|------|------|
| Wind power accommodation capacity (GW)      | 19.96| 21.26| 22.21| 22.71|
| Actual installed capacity (GW)              | 2.68 | 8    | 16.64| 40   |

With peak regulation constraints, the wind power accommodation capacity of Guangdong power grid is enough to accommodate the wind power planned in 2020 and 2025 while it is different in 2030. In 2030, the wind power cannot be completely accommodated during valley load period, and the difference from the actual installed capacity is 17.29 GW, accounting for 43.23% of the total.
3.2. The Result of Sensitivity Analysis

Based on the predicted load in section 2.1 and the parameter values in section 2.3, the model in section 2.1 is used to calculate the change rate of wind power accommodation capacity when the coefficient of peak regulation to the tie-line power (CPRT), the load reserve ratio (LRR), the minimum output power coefficient (MOPC) and the simultaneity factor of the wind power output (SFWP) change from 1% to 10%.

The results are shown in figure 4, where the wind power accommodation capacity is represented by WPAC. The part (a), (b) and (c) in figure 4 show the conditions of 2020, 2025 and 2030, respectively, which is the same in figure 5.

From the view of sensitivity in the three years, the sensitivity of MOPC is the maximum (slopes are 3.46, 4.13, 4.74, respectively) while SFWP is the minimum (slopes are 1.84). The other 2 parameters compared, the sensitivity of LRR is smaller firstly and then larger (slopes are 2.82, 3.43, 4.03, respectively) while CPRT is the opposite (slopes are 3.15, 3.39, 3.68, respectively)
In terms of adjustability, SFWP is related to the wind energy quality of wind farms, the type of wind turbines and so on, so the adjustment is contrary to the original intention of building wind farm; LRR is related to the reliability requirement of power grid, it cannot be adjusted at will; CPRT is related to the proposed transmission protocol, the adjustment needs power grid to be coordinated with each other; MOPC is related to the power supply structure and it changes with peak regulation ability of power supply system, it can be adjusted only by Guangdong Province.

To sum up, SFWP has the lowest sensitivity, weak adjustability and the adjustment of the other three parameters are to improve the wind power accommodation capacity by increasing the peak-regulation margin of power supply system. Therefore, the other three parameters are combined in pairs to study the effect of multi-factor coupling. There is the ratio of coupling effect and the sum of individual effect in figure 5. It shows that the coupling effect of MOPC and LRR is less than the sum of the two, the ratio of these two parameters changes with year and parameter value, the variation range is 0.885-0.989. The coupling effect of the other two pairs is equal to the sum of individual effect. In short, the coupling effect is no more than the sum of individual effect, so the multi-factor coupling is not considered. Thus, MOPC is the best one among the four parameters from the perspective of sensitivity and adjustability, which is related to peak regulation ability of the power supply system. Because of the good performance of reducing peak and filling valley, the energy storage system is used to improve the wind power accommodation capacity.

3.3. The Result of Energy Storage System Configuration in 2030
With peak regulation constraints, the wind power planned can be fully accommodated in 2020 and 2025 while it is different in 2030 (section 2.1), so the energy storage stations are needed only in 2030 to improve the wind power accommodation capacity. In addition, the wind power can be fully accommodated during valley load period in the summer of 2030, considering the loss only for wind power accommodation so the days with loss cost take 90. The problem of energy storage system configuration is done by the method in section 2.2.

Where PS is the representation of the proportion of scheme. Unbalanced power is the basis of energy storage system configuration so that all schemes in table 4 can solve the problem of insufficient capacity for power grid to accommodate wind power during valley load period. In scheme 1–5, it is assumed that the result can be put into practice and the scheme 1 which is a composite energy storage system is set to be a comparison scheme to study the economic performance of different kinds of energy storage. In scheme 6, the constraints of CAES construction and SCES construction are added. Scheme 7 is based on scheme 1, and the days with loss cost is set as 365 to study the effect of loss cost.

The results in table 4 show that: the design capacity of CAES is more than 98% in lower cost schemes (scheme 1, 2, 4, 5) and it reaches the upper limit with the geographical constraint (scheme 6), while the efficiency of CAES is the lowest (0.65), which means that the life cycle annual cost of CAES is the lowest when storing the same amount of electricity; it is needed to increase the capacity of power-type storage to store energy before CAES is turned on and to smooth power fluctuations after CAES is turned on if BS is not set, the cost of scheme 2 is even higher than scheme 1 without taking into account the power fluctuations of power grid after CAES is turned on; the cost of scheme 3 that only BS is used as energy-type storage is about 0.72 times higher than the cost of scheme 1; in the case of the same energy-type storage configuration results, the total cost of only SCES is used as power-type storage is 0.55% (74 million yuan) lower than that only FES is used, the value is very low compared with the total cost, but the value of power only accounts for 5.97% and capacity is less than 0.01%; in addition, the capacity of SCES almost reaches the upper limited in scheme 6. In a word, it is an effective way to reduce the cost by taking CAES with the large-capacity and BS as energy-type storage, and only SCES is used as power-type storage plays an active role in reducing cost.
Therefore, without considering the constraints of energy storage construction, scheme 5 is the best one with the life cycle annual cost of 13.53 billion yuan and the efficiency of 63.62%, the power of BS, CAES and SCES account for 8.63%, 85.40%, 5.97% and the capacity account for 1.61%, 98.39%, 3.8e-6, respectively.

4. Conclusion and Discussion

According to the parameters and constraints taken in this paper, enumeration method is adopted to solve the problem of energy storage system configuration, and the conclusions are as follows: power grid cannot fully accommodate the wind power with peak regulation constraints in 2030 if the wind power in Guangdong is developed as it planned, and the capacity that can be accommodated is quite different from the actual installed capacity, with the difference accounting for 43.23% of the total installed capacity; the minimum output power coefficient is not only the most sensitive (slopes are 3.46, 4.13, 4.74) but also the most adjustable in the four parameters so that it is chosen to be adjusted to improve the wind power accommodation capacity; the proportion of design power and capacity of CAES are 85.40% and 98.39%, the proportion of design power and capacity of BS are 8.63% and 1.61%, and the rest is SCES, such energy storage system has the best economic performance with the life cycle annual cost of 13.53 billion yuan.

Based on the actual conditions of Guangdong, the constraints of resources may make CAES difficult to put into practice, the salt cavern and some other places for its construction are also needed for gas storage and oil storage to ensure sufficient energy supply as well as obtaining economic income. It’s necessary to calculate the opportunity cost of the construction of CAES and others that

Table 4. The result of energy storage system configuration.

| Schemes | Power (MW) | Capacity (MWh) | Power (MW) | Capacity (MWh) | Power (MW) | Capacity (MWh) | Power (MW) | Capacity (MWh) | Life cycle annual cost (billion yuan) | Efficiency (%) |
|---------|------------|----------------|------------|----------------|------------|----------------|------------|----------------|-------------------------------------|----------------|
| Scheme 1 | 775.98     | 633.35         | 38         | 833.45         | 536.29     | 0.15           | 0.41       | 1.4e-4         | 13.5329                             | 63.62          |
| Scheme 2 | /          | /              | /          | /              | 859.98     | 59.99          | 0.06       | 5.9e-3         | 13.5362                             | 63.37          |
| Scheme 3 | 9          | 44             | /          | /              | 536.29     | 0.15           | 0.41       | 1.4e-4         | 23.2691                             | 82.83          |
| Scheme 4 | 775.98     | 633.35         | 38         | 833.45         | /          | /              | 536.70     | 0.19           | 13.6068                             | 63.62          |
| Scheme 5 | 775.98     | 633.53         | 38         | 833.45         | /          | /              | 536.70     | 0.15           | 13.5328                             | 63.62          |
| Scheme 6 | 8          | 853.14         | 374.63     | 500            | 9.62       | 2.6e-3         | 527.07     | 0.18           | 20.0103                             | 76.26          |
| Scheme 7 | 775.98     | 633.53         | 7          | 679.70         | 536.29     | 0.15           | 0.41       | 1.4e-4         | 17.4428                             | 63.62          |

PS 1 (%) 8.63 1.61 85.40 98.39 5.96 3.8e-6 4.6e-3 3.6e-9
PS 2 (%) / / 90.68 99.85 9.32 0.15 6.2e-6 1.5e-7
PS 3 (%) 94.60 100.00 / / 5.39 3.4e-6 4.1e-3 3.2e-9
PS 4 (%) 8.63 1.61 85.40 98.39 / / 5.97 3.8e-6 / /
PS 5 (%) 8.63 1.61 85.40 98.39 5.97 3.8e-6 / /
PS 6 (%) 89.52 68.86 5.05 31.14 0.10 6.1e-8 5.33 4.2e-6
PS 7 (%) 8.63 1.61 85.40 98.39 5.96 3.8e-6 4.6e-3 3.6e-9

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Taking into account technical progress, a 10 MW class demonstration platform of non-traditional CAES has built in China so it may be put into commercial use by 2030. The gas storage system of non-traditional CAES is gasholder, non-traditional CAES is not limited by the geographical conditions but the investment cost may be increased because of the difference in gas storage device. In the meantime, the cost of other kind of energy storage may reduce, so the technical function coefficient can be added to the objective function for energy storage system configuration. Moreover, it is easy to cause damage to the components of super capacitor due to the high relative humidity of Guangdong. The humidity can be linked with the life cycle of super capacitor and the replacement cost coefficient may be added to the objective function in the calculation of initial investment cost in the subsequent research. Finally, the wind power accommodation capacity is not only related to the power but also related to the load, and it can take measures such as adjusting the power consumption time of large factories to increase the valley load, that is, increasing peak-regulation margin through demand side management.

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