Research on the accommodation of clean energy considering storage and demand respond system

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Abstract. This paper builds a power supply system including wind power, PV, storage and demand-side response. Taking the largest amount of clean energy consumption as the primary goal, considering the costs of power supply, adding power balance, grid reliability, upper and lower limits of the energy storage system, demand-side response, and wind power and PV output limits, the study intends to distinguish the different power price development models. It establishes four scenarios including energy storage system and demand-side responses not considered, only energy storage, only demand-side responses, energy storage system and demand-side response are considered simultaneously. Through comparative analysis, the energy storage and the demand-side response can effectively improve the wind power and PV consumption rate about 10% and improve the power supply stability and economy. Establish a penalty mechanism on the demand-side response, shift the load, reduce the power purchase from grid, and save about $2230 by the simulation. This method can enhance the flexibility and reliability, effectively reduce the peak value, reduce the cost of power purchase.

1. Introduction
China is facing a crucial period of energy transformation and development. How to effectively use energy, reduce total energy consumption, and increase terminal energy efficiency are the key tasks of Chinese energy development strategy. From the perspective of realizing the sustainable development of the energy industry, the large-scale volatility of clean energy access to the power grid has brought great challenges to its safe and stable operation. The traditional energy supply model affected by the rapid development of clean energy, the abandoning winds in some areas is frequent, and the inverse relationship between clean energy supply and power load occurs [1-4]. The study is to allocate energy storage capacity to combine local actual loads with wind power and PV to establish a stochastic scenario and verify the effectiveness of storage capacity [5-6]. Establish a penalty mechanism for demand-side response, shift the load, reduce the power purchase from grid, reduce the cost of power purchase. It intends to distinguish the different development models of power prices at peak-time, and constructs a method based on price elasticity of electricity prices and multi-period electricity price response. It proposes a charge-discharge strategy for energy storage systems and an optimal operating strategy for wind power and PV; introduces demand-side responses to regional grids [7-8].
2. The basic structure and model

2.1. PV model
PV model is related to the output power, light intensity, and ambient temperature under standard rated conditions [9-10].

\[ P_o = P_{STC} \frac{G_c}{G_{STC}} [1 + k(T_c - T_{STC})] \]  

(1)

Where, \( P_o \) is actual output power, STC is solar irradiance, \( G_{STC} \) is working point irradiance, \( k \) is power temperature degree, \( P_{STC} \) is rated output power, \( T_c \) indicates the actual temperature of the operating point.

2.2. Wind model
Wind power is related to wind speed. Normally, it can be represented by:

\[ P_W = \begin{cases} \frac{P_r}{v_C-v_r} & v_C < v < v_r \\ P_r & v_r < v < v_f \\ 0 & v_f < v \text{ or } v > v_f \end{cases} \]

(2)

Where, \( P_W \) is wind output power, \( P_r \) is wind rated, \( v_C \) is cut in wind speed, \( v_r \) is rated wind speed, \( v_f \) is cut out wind speed.

2.3. Storage model
Battery is discharged, charge and discharge power at \( t \), \( P_{SB}(t) \geq 0 \), the remaining capacity of the battery \( S(t) \) at \( t \):

\[ S(t) = S(t-1)(1 - \sigma) - P_{SB}(t) / \mu_p \]

(3)

Battery is charged, charge and discharge power at \( t \), \( P_{SB}(t) \leq 0 \), the remaining capacity of the battery \( S(t) \) at \( t \):

\[ S(t) = S(t-1)(1 - \sigma) - P_{SB}(t) / \mu_c \]

(4)

Where, \( S(t) \) is the capacity at the previous moment, the remaining capacity of the battery before use, \( S(t-1) \) is the battery remaining capacity at the next moment, \( \sigma \) is battery self-discharge per unit time, \( \mu_c, \mu_p \) are charge and discharge efficiency, \( \sigma \) is battery self-discharge rate.

2.4. Demand-side response
The demand-side response is to make the load closer to the timing of the wind power and PV by changing load transferred time, contributing to grid integration of wind power and PV, reducing the need for configuration of the energy storage system, improving the power grid economic efficiency. Use 24 hours per day as the demand-side response period, requiring the transferable load satisfying to one day. Part of the peak load will be transferred to a sufficient period of wind power and PV, so that the load, wind power and PV are closer to time sequence. Users who participate in the demand-side response and change the load according to economic incentives [11-12]. The compensation fee is:

\[ C_{SR} = \sum_{t=1}^{n} \rho L_{in,t} = \sum_{t=1}^{n} \rho L_{out,t} \]

(5)

Where, \( \rho \) is the compensation factor for transferring load, \( L_{in,t} \) is the transferred-in load at \( t \), \( L_{out,t} \) is the transferred-out load at time \( t \). When the renewable energy output is greater than the load, \( L_{in,t} \geq 0, L_{out,t} = 0 \). When the renewable energy output is smaller than the load, \( L_{out,t} \geq 0, L_{in,t} = 0 \).

3. Model of clean energy consumption considering storage and demand respond

3.1. Objective function
It aims to optimize the target of wind power and PV consumption and maximize system operation cost, establish an integrated optimization and absorption algorithm including wind, PV, storage and
demand-side response, forming optimization clean energy maximum consumption model. The primary goal of maximally dissipating wind power and PV:

\[
\min \left[ - \sum_{t=1}^{N} (P_{L,t} + P_{S,t}^+) + \varepsilon \sum_{t=1}^{N} (eP_{N,t} + \rho L_{in,t}) \right]
\] (6)

\(N\) is the number of scheduling cycles. \(P_{L,t}\) is the load of wind power and PV consumption by the load at time \(t\). \(P_{S,t}^+\) is dissipating wind power and PV charging to storage system at time \(t\). \(\varepsilon\) is the price purchased from the grid is $89.5/MWh, \(P_{N,t}\) is request power from the grid at \(t\), \(P_{P,t}\) is the load at time \(t\). \(L_{in,t}\) is the load of time \(t\).

If the value \(\varepsilon\) is too large, the impact of the operating cost in the objective function will be greater than the wind power and PV consumption. If the value is too small, the impact of the operating cost will be too small to be negligible. \(\varepsilon\) is $89.5/MWh, \(\rho\) is $1.5/MWh, \(\varepsilon\) is \(10^{-3}\), the operating cost of the impact factor is less than 1.

If \(P_{W,p,t} \geq L_t, P_{W,p,t} = L_t\); if \(P_{W,p,t} < L_t, P_{W,p,t} = P_t\). So, the wind power and PV consumption at time \(t\).

\[
P_{L,t} = \min(P_{W,p,t}, L_t)
\]

(7)

If \(P_{W,p,t} \geq L_t, P_{N,t} = 0; \) if \(P_{W,p,t} < L_t\).

\[
P_{N,t} = L_t - P_{P,t} - P_{S,t}^+
\]

(8)

3.2. Constraint conditions

Power balance constraints:

\[
P_{W,P,t} = P_{N,t} + P_{S,t}^+ = L_t - L_{out,t} - L_{in,t} + P_{S,t}^+-
\]

(9)

Reliability Constraints: To ensure stable operation while off-grid, energy can be stored at capacity limitation, the energy stored at \(t\):

\[
S_{min} \leq S_t \leq S_{max}
\]

(10)

When the off-grid \(S_{min}\), the minimum storage capacity ensure stable operation of PV connection for 0.5 h. \(S_{max}\) is the maximum storage capacity.

The storage system constraints: The real-time power of the charging and discharging is subject to a certain upper limit:

\[
0 \leq P_{S,t}^+ \leq P_{S,t,max}
\]

(11)

\[
0 \leq P_{S,t}^- \leq P_{S,t,max}
\]

(12)

\(P_{S,t,max}\) and \(P_{S,t,max}\) are the upper limit of the charging and discharge storage power at \(t\) respectively.

The charging power of storage system is also affected by wind power and PV output and load:

\[
P_{S,t}^+ \leq P_{W,P,t} - L_t
\]

(13)

The discharge power of storage system is also affected by the remaining power:

\[
P_{S,t}^- \leq S_t - 1
\]

(14)

Network security constraints: The power flow of each branch needs to be set at the limit.

\[
P_{B,i,t}^{min} \leq P_{B,i,t} \leq P_{B,i,t}^{max}
\]

(15)

\(P_{B,i,t}\) is the trend of branch \(i\) at \(t\), \(P_{B,i,t}^{max}\) and \(P_{B,i,t}^{min}\) are the upper bound trend and the lower bound trend of the branch \(i\). Demand-side response constraints: The demand-side response changes the power consumption, improves the terminal’s power consumption efficiency, reduces the terminal’s power consumption, forming a virtual generator set, participating in system scheduling. The limit of the transferable load is:

\[
0 \leq L_{in,t} \leq t_{in}^{max}
\]

(16)

\[
0 \leq L_{out,t} \leq L_{out}^{max}
\]

(17)

\(L_{in}^{max}\) is the upper bound of transfer-in load at \(t\). \(L_{out}^{max}\) is the upper bound of transfer-out load at \(t\).

In one distribution cycle, the total transfer-in load equal to the total transfer-out load:

\[
\sum_{t=1}^{N} L_{in,t} = \sum_{t=1}^{N} L_{out,t}
\]

(18)

Wind power and PV output constraints:

\[
0 \leq P_{W,P,t} \leq P_{W,P}^{max}
\]

(19)
$P_{W,F}^{max}$ is the maximum value for the active power of wind power and PV.

4. Model solving analysis

In order to solve the problem of constraints of wind power and PV consumption, this study adopts an improved empire competition algorithm. It simulates the competition between the human political society, the empire in the colonial phase and expands their power by occupying colonies. It is divided into three processes: initial state creation, assimilation and revolution. As an example, the method and steps for improvement are explained. Two conditions for determining, wind power and PV output are greater than the original load, the total load transferred into a cycle is equal to the total amount of transferred load are added, shown in Figure 1.

![Figure 1. Improved empire competition algorithm flowchart.](image)

5. Scenario simulation and analysis

Through the addition of storage system (lithium iron phosphate battery and flow battery) and demand-side response control, excess power is stored during periods when wind power and PV are high, demand-side responses are used to flexibly transfer loads, post-transition power load are used to approximate the combined output of wind and PV to maximize the consumption. Clean energy can not only solve the problem of abandoning, but also reduce the power purchase through penalties.

5.1. Hybrid System Operation Control Strategy Analysis

1) In daytime, the wind speed is greater than wind turbine, the PV panel and wind turbine have outputs, shown in Table 1. The ideal situation is that PV panel and wind turbine have output. There is a transitional state in a short period of time, which is the key issue solved in the control strategy.

2) The PV panel has no output and the wind turbine has output, such as in the windy night, or in the cloudy days, shown in Table 2. Only the wind turbine has power output. In the operating mode, the total power generation, load consumption, and the power characteristics must be considered by two conditions of the wind, PV simultaneously, and only wind powered.

3) When the PV panel has power output and wind turbine has no power output, no wind and sunshine.
Table 1. Wind and PV supply and operation.

| model | wind | PV | load | storage | distribution |
|-------|------|----|------|---------|--------------|
| 1     | ✓    | ✓  | ✓    | ✓       | standby      |
|       |      |    |      | Power generation is greater than load charging |             |
|       |      |    |      | Ideal operation mode, battery and distribution are in waiting mode |             |
| 2     | ✓    | ✓  | ✓    | ✓       | activated    |
|       |      |    |      | Power generation is greater than load charging |             |
|       |      |    |      | When PV, wind, and battery are insufficient, distribution is activated |             |
| 3     | ✓    | ✓  | ✓    | ✓       | standby      |
|       |      |    |      | Power generation is greater than the load discharging |             |
|       |      |    |      | When PV and wind are insufficient, battery is discharging |             |
| 4     | ✓    | ✓  | ✓    | ✓       | activated    |
|       |      |    |      | Power generation is greater than load discharging |             |
|       |      |    |      | PV and wind output are insufficient, the battery has been in deep discharge, start the distribution |             |
| 5     | ✓    | ✓  | ✓    | ✓       | standby      |
|       |      |    |      | Power generation is less than load discharging |             |
|       |      |    |      | PV and wind are insufficient, the battery is discharging, distribution is waiting |             |
| 6     | ✓    | ✓  | ✓    | ✓       | activated    |
|       |      |    |      | Power generation is less than load discharging |             |
|       |      |    |      | PV and wind output are sufficient, the battery is discharging to default, distribution is activated |             |
| 7     | ✓    | ✓  | ✓    | ✓       | standby      |
|       |      |    |      | Power generation is less than load charging |             |
|       |      |    |      | PV and wind output are sufficient, the battery is charging, distribution is waiting |             |
| 8     | ✓    | ✓  | ✓    | ✓       | activated    |
|       |      |    |      | Power generation is less than the load charging |             |
|       |      |    |      | PV, wind and battery are insufficient, distribution is activated |             |

4) When the PV and wind have no power output, such as at night without wind or cloudy day. Grid-connected is the supplement, off-grid batteries must be started to provide power. In fact, batteries in grid-connected energy systems are expected to have longer cycle life.

5.2. Clean energy consumption ratio estimation
Through the four scenarios comparison, power purchase cost adding storage and demand-side response to verify the model correctness and effectiveness. The wind power installed capacity is 20MW, the PV installed capacity is 20MW.
In storage system, \( S_{\text{max}} = 20 \text{ MW}, S_{\text{min}} = 1 \text{ MW}, P^+_{S,j,\text{max}} = 6 \text{ MW}, P^-_{S,j,\text{max}} = 6 \text{ MW} \).

In demand-side respond system, \( L^+_{\text{in}} = 6 \text{ MW}, L^-_{\text{in}} = 6 \text{ MW}, \rho = 10 \).

The distributed PV output exceeds the load at 8-17 hours, the peak period around 20:00. At this time, PV output has dropped to zero. Wind power output will have greater volatility. The common feature is relatively stable at 8-16, at night is relatively strong. The other time operation are shown in Table 3 and 4. In order to study the impact of storage systems and demand-side response on consumption, four scenarios were established:

**Table 3. PV supply and operation.**

| model | wind | PV | load | storage | distribution |
|-------|------|----|------|---------|--------------|
| 17    | ○    | √  | Power generation is greater than load | charging | standby      |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 18    | ○    | √  | Power generation is greater than load | charging | activated   |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 19    | ○    | √  | Power generation is greater than load | discharging | standby      |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 20    | ○    | √  | Power generation is greater than load | discharging | activated   |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 21    | ○    | √  | Power generation is less than load | discharging | standby      |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 22    | ○    | √  | Power generation is less than load | discharging | activated   |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 23    | ○    | √  | Power generation is less than load | charging | standby      |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 24    | ○    | √  | Power generation is less than load | charging | activated   |
|       |      |    |      |         |              |
|       |      |    |      |         |              |

**Table 4. PV and wind have no power supply.**

| model | wind | PV | load | storage | distribution |
|-------|------|----|------|---------|--------------|
| 25    | ○    | ○  | Power generation is less than load | discharging | standby      |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 26    | ○    | ○  | Power generation is less than load | discharging | activated   |
|       |      |    |      |         |              |
|       |      |    |      |         |              |
| 27    | ○    | ○  | Power generation is less than load | charging | activated   |
|       |      |    |      |         |              |
|       |      |    |      |         |              |

Scenario 1: The storage and demand-side response are not operating;
Scenario 2: The storage is not running, the demand-side responds to the operation;
Scenario 3: Storage operation, demand-side response is not running;
Scenario 4: Both storage and demand-side response are running, four scenarios shown in Table 5.

**Table 5.** the consumption and operation results.

| scene | Maximum net power(MW) | Minimum net power(MW) | Power purchased (MW) | Purchase price ($) | PV consumption rate(%) | wind consumption rate(%) | Objective function value |
|-------|------------------------|-----------------------|----------------------|--------------------|------------------------|--------------------------|--------------------------|
| 1     | 10.4                   | -10.6                 | 99.1                 | 8875               | 60.09                  | 58.01                    | -29.54                   |
| 2     | 9.2                    | -9.7                  | 91.5                 | 8190               | 64.91                  | 56.02                    | -48.03                   |
| 3     | 10.4                   | -10.6                 | 81                   | 7254               | 71.58                  | 67.33                    | -60.07                   |
| 4     | 9.2                    | -10.4                 | 76.5                 | 6852               | 77.98                  | 68.01                    | -72.46                   |
5.3. Storage system
Comparing Scenario 1 and 3, the introduction of storage system increased the wind power and PV consumption rate from 60.09% to 71.58%, and the power purchased from grid is reduced from 99.1MW to 81.0MW, from $8875 dropped to $7254, which means that a scheduling cycle of storage system can save $1620896 in expenditure for operations. Comparative scenario 2 and 4, adding demand-side response and storage system in wind power and PV consumption rate is even more evident, from 4.91% to 77.98%. However, the construction and operation of storage system requires a certain cost, and rational configuration of storage system will greatly increase the economic, efficiency and reliability. In scenario 4, the charging and discharging of storage system during a scheduling period is shown in Table 6.

Table 6. the storage charging and discharging results.

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| t  | 1  | 2  | 3  | 4  | 5  | 6  |
| $P_{S,t}^+$ | 0  | 0  | 0  | 0  | 0  | 0  |
| $P_{S,t}^-$ | 0  | 0  | 0  | 0  | 0  | 0  |
| t  | 7  | 8  | 9  | 10 | 11 | 12 |
| $P_{S,t}^+$ | 0  | 0  | 0.1| 0.9| 5.6| 6  |
| $P_{S,t}^-$ | 0  | 0  | 0  | 0  | 0  | 0  |
| t  | 13 | 14 | 15 | 16 | 17 | 18 |
| $P_{S,t}^+$ | 5.9| 0.6| 0  | 0  | 0  | 0  |
| $P_{S,t}^-$ | 0  | 0  | 0  | 0  | 3.4| 5.5 |
| t  | 19 | 20 | 21 | 22 | 23 | 24 |
| $P_{S,t}^+$ | 0  | 0  | 0  | 0  | 0  | 0  |
| $P_{S,t}^-$ | 1.1| 1.6| 2.2| 0.1| 0.3| 0.4|

Table 6 shows in daytime wind power and PV output are greater than the load, storage is charged, the charging stopped at maximum capacity 20 MW. When the wind power and PV output gradually decrease to zero at night, storage system discharged to the load, the insufficient amount purchased from grid, discharge is stopped when the stored energy drops to 1 MW. Surplus wind power and PV output during the day are stored for use at night to absorb excess wind power and PV output during the day and reduce the amount of purchased from grid at night, reducing the operating cost, shown in Figure 2.

5.4. Demand-side respond
Comparing Scenario 1 and 2, the demand-side response has increased the wind power and PV consumption rate from 60.09% to 64.91%, the power purchased from the grid has been reduced from 99.1MW to 91.5MW. From $8875 dropped to $8190, means that the demand side can respond to a scheduling cycle saving $685 in expenditure. The comparison of Scenario 3 and 4 finds that the
introduction of the demand-side response for the wind energy and PV consumption rate increases more significantly from 71.58% to 77.98%. In scenario 4, the load transfer during a scheduling period is shown in Table 7.

Table 7. demand responds.

| t  | 1 | 2 | 3 | 4 | 5 | 6 |
|----|---|---|---|---|---|---|
| Li  | 0 | 0 | 0 | 0 | 0 | 0 |
| Lo  | 0 | 0.5 | 0.6 | 1.5 | 1.3 | 0 |
| t  | 7 | 8 | 9 | 10 | 11 | 12 |
| Li  | 0 | 0 | 0.2 | 1.3 | 1.8 | 0.4 |
| Lo  | 0.2 | 0 | 0 | 0 | 0 | 0 |
| t  | 13 | 14 | 15 | 16 | 17 | 18 |
| Li  | 2 | 0.7 | 1.7 | 0 | 0 | 0 |
| Lo  | 0 | 0 | 0 | 0.4 | 0 | 0.7 |
| t  | 19 | 20 | 21 | 22 | 23 | 24 |
| Li  | 0 | 0 | 0 | 0 | 0 | 0 |
| Lo  | 1.1 | 0.2 | 0.3 | 0 | 1.5 | 0.5 |

Table 7 showed that wind power and PV output gradually decrease to the minimum at night, it is exactly the peak load period of a cycle, the load is transferred out. when the daytime wind power and PV output are greater than the load, load transferred out. Part of the load during the night rush hour is shifted to the period during which day wind power and PV output are greater than the load, excess wind power and PV output during the day, reduce power purchased from grid, reducing wind power and PV and operating costs. Figure 3 showed that with demand-side response, part of the load at night when the PV output is low transferred to the daytime. When the wind power and PV output are larger than load, the wind power and PV output are removed. The net power of the load becomes smaller, so that the load curve is closer to the wind power and PV output curve in time series and is closer to the primary goal of “self-use” for wind power and PV generation.

6. Conclusions
This paper proposes a method of introducing storage and demand-side response. To verify the role of storage and demand-side response in improving wind power and PV efficiency, four scenarios were set up and verified by comparative analysis. The results show: (1)The storage can significantly increase wind power and PV consumption rate, reduce the power amount purchased from the grid. (2)The demand-side response can improve the wind power and PV consumption rate. Load structure can be changed so that the load curve is closer to the output curve of wind power and PV, and clean energy can be largely consumed. (3)Simultaneous introduction of storage system and the demand-side response can make the two more effective in increasing the PV consumption rate.

Reference
1. Ji Y, Ai Q, Xie D 2010 Power System Technology 34 15-23
2. Zhu X, Han X Q, Qin W P 2015 Renewable and Sustainable Energy Reviews 42 453-1463
3. Wu X, Yin X G, Song X 2013 Energy and Power Engineering 4 142-149
4. HOSSEINI S, AL KHALED 2017 A Applied Soft Computing 24 1078-1094
5. Xu J, Sui J, Li B 2016 Energy 35 4361-4367
6. Cho H, Smith A D, Mago P 2014 Applied Energy 136 168-185
7. Luo F.a, Wei G.a , Xu X.b, Lu Y.c 2016 Journal of Computational and Theoretical Nanoscience 13 1933-1938
8. Zhang D, Wang J 2016 Dianwang Jishu/Power System Technology 40 451-458
9. Ming W., Jian S, Liu H, Yang L, Yu J 2014 POWERCON 2014 - 2014 International Conference on Power System Technology: Towards Green, Efficient and Smart Power System, Proceedings 3361-3365
10. Zeng Z, Zhao R, Yang, H, Tang S 2014 Renewable and Sustainable Energy Reviews 701-718
11. Hu J, Huang B 2012 Implementation effect evaluation power supply 33 80-84
12. FENG L, ZHANG J, LI G 2010 Protection and Control of Modern Power Systems 1