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RESEARCH ON CAPACITY CONFIGURATION AND COMPREHENSIVE BENEFIT OF WIND-PHOTOVOLTAIC-STORAGE HYBRID POWER SYSTEM BASED ON GRAVITY ENERGY STORAGE

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ABSTRACT

In the wind-photovoltaic-storage hybrid power system based on gravity energy storage, a capacity optimization configuration method is proposed. Firstly, the capacity optimization configuration model of wind-photovoltaic-storage hybrid power system is established. Secondly, under the condition of different gravity energy storage capacity, the cat swarm optimization is used to optimize the capacity configuration of wind farm and photovoltaic power station. The optimal configuration meets the following indicators: utilize the complementary features of wind and photovoltaic, reduce the loss rate of power supply, increase the contribution rate of wind and photovoltaic, and ensure the minimum total cost of the system. Thirdly, the simulation analysis is carried out with data from a certain area of Gansu Province, China. The simulation results show that the proposed capacity optimization configuration method is reasonable and effective.

Keywords: wind-photovoltaic-storage hybrid power system, gravity energy storage, capacity optimization configuration, evaluation index

1. INTRODUCTION

In China, wind and solar resources are relatively abundant, especially in the northwestern area. The installed capacity of renewable energy in the northwest have been increasing these years, but there is a serious problem of abandoned wind power and solar [1].

Energy storage technology is an important method to meet large-scale access to renewable energy. Gravity energy storage system (GESS), as a unique energy storage way, can depend on the mountain, which is a natural advantage in the northwest China [2]. GESS uses the height of the mountain to store energy. Its construction can adapt to the changes of the terrain. The energy storage carrier is heavy object. It not only can be recycled, but also will hardly pollute the environment. And its construction conditions are not limited by the geographical environment like pumped storage. Therefore, the future application prospects are broad.

The wind-photovoltaic hybrid power system with energy storage system can effectively improve energy utilization density and improve the capacity of wind power and photovoltaic power generation. At present, scholars have carried out some research on the wind-photovoltaic-storage hybrid power system (WPS-HPS). [3] considered the independent and grid-connected modes. The capacity configuration problem of WPS-HPS was studied. However, this study used batteries as the energy storage system, which was theoretically difficult to meet the needs of larger projects. [4] analyzed the individual wind power system, photovoltaic system and WPS-HPS. The economic and environmental friendliness of each system were compared. The wind-photovoltaic-pumped storage hybrid power system was established under the condition of isolated network operation [5]. The optimal determination method of pumped storage capacity was determined by comparing the operating states of pumped storage power stations with different capacities. However, there was no relevant research on the capacity of wind power system and photovoltaic system in the hybrid power system. [6] studied the capacity configuration of pumped storage system under the condition of the wind-photovoltaic hybrid power system. But only the purchase and sale efficiency was considered when studying economics, and the initial cost of the pumped storage system installation were not considered.

At present, the research on the capacity configuration of WPS-HPS did not involve the capacity of wind farm (WF), photovoltaic power station (PVPS) and GESS as the optimization variables. Therefore, a capacity optimization configuration method is proposed in the WPS-HPS based on GESS. Firstly, the model of GESS and the capacity optimization configuration model of WPS-HPS are established. Secondly, in the case of different GESS capacity, cat swarm optimization is used to optimize the system capacity configuration and the optimal configuration meets the evaluation index. At the same time, this paper chooses a relatively good capacity configuration. Thirdly, the simulation analysis is carried out with data from a certain area of Gansu Province, China. The simulation results show that the proposed capacity optimization configuration method is reasonable and effective.

2. THE WPS-HPS

This paper studies the WPS-HPS, which is consisting of WF, PVPS, GESS and load. The system structure is shown in Fig 1.

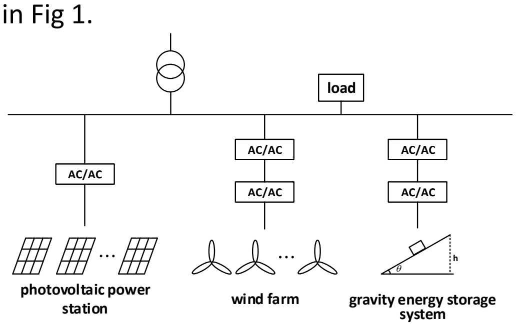

Fig 1 The WPS-HPS

This paper adopts the WF model in [7] and the PVPS model in [8]. We mainly establish the GESS model as follows.

GESS means that when the load is low, motors drive the heavy object to a certain height and the system completes energy conversion from electrical energy to kinetic energy, and then gravitational potential energy. Electrical energy is stored in the form of gravitational potential energy. When the load peaks, the heavy object at a certain height is released, which drives generators to work. The system completes the energy conversion from gravitational potential energy to kinetic energy, and then electric energy. The energy conversion of the GESS is shown in Fig 2.

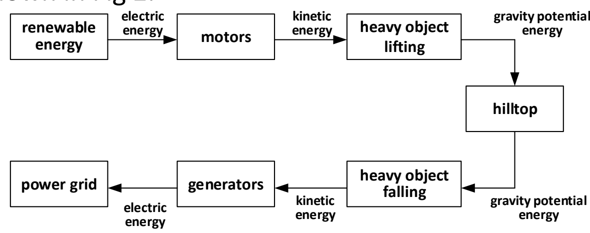

Fig 2 Energy conversion diagram of GESS

(1) Storage energy process

The amount of energy stored and released by the GESS is related to the height, slope and weight of the mountain. When the system stores energy, motors work and consume electrical energy, and the heavy object is pulled from the mountain to the top of the mountain by the pulley block. During the process, the gravitational potential energy increases and is finally stored at the top of the mountain. When the heavy object rises, its speed is maintained. The force balance expression of the heavy object satisfies:

$$F_{\mathrm{m}}=\mathrm{mg}\cdot\sin\theta+F_{\mu} \tag{1}$$

$$F_{\mu}=\mu\cdot\mathrm{mg}\cdot\cos\theta \tag{2}$$

Where F_{m} is motor traction, F_{μ} is friction, m is quality of the heavy object, g is gravitational acceleration, θ is slope, μ is the coefficient of friction.

$$P_{\mathrm{m}}=F_{\mathrm{m}}\cdot v_1=\left(\mathrm{mg}\cdot\sin\theta+F_{\mu}\right)\cdot v_1 \tag{3}$$

Where P_{m} is motor power, v_1 is rising speed.

(2) Release energy process

The process of releasing energy is more complicated than the process of storing energy. The GESS releases the heavy object from the top to the bottom of the mountain by the pulley block. The process is divided into an acceleration phase and a grid-connecting phase. During the process, the gravitational potential energy is reduced, which drives generators to generate electric energy to the power grid.

During the acceleration phase, the speed of heavy object gradually accelerates from zero. At this time, generator output is unstable and cannot be connected to power grid. During the grid-connecting phase, heavy object accelerates to a constant speed and keeps the constant speed to fall. So generator output can keep the balance. In order to keep heavy object falling at a constant speed and protect device, motors also work. The force balance expression of the heavy object satisfies:

$$\text{mg}\cdot\sin\theta = F_{\mu} + F_{\text{m}} + F_{\text{g}} \tag{4}$$

$$F_{\mu} = \mu\cdot\text{mg}\cdot\cos\theta \tag{5}$$

Where F_{g} is generator traction. This paper assumes that motor traction is zero, which means that motors do not work during releasing energy.

$$P_{\text{g}} = F_{\text{g}}\cdot v_2 \tag{6}$$

Where P_{g} is generator power, v_2 is sliding speed.

This paper assumes that the slop and quality of the heavy object are known and the height of mountain is the only factor affecting capacity of GESS to study capacity of WPS-HPS. Ideally, the energy stored by GESS is expressed by (7).

$$W = \text{mg}\cdot h \tag{7}$$

Where h is the height of mountain.

3. THE CAPACITY OPTIMIZATION CONFIGURATION MODEL OF WPS-HPS

3.1 Evaluation index

(1) Complementary features of wind and photovoltaic

The sum of the output power of wind and photovoltaic relative to the fluctuation of the load reflects the complementary features of wind and photovoltaic, which is defined as

$$D = \frac{1}{\overline{P_{\text{L}}}}\sqrt{\frac{1}{24}\sum_{t=1}^{24}\left(P_{\text{w}}(t) + P_{\text{p}}(t) - P_{\text{L}}(t)\right)^2} \tag{8}$$

Where $\overline{P_{\text{L}}}$ is average power of load, $P_{\text{w}}(t)$ is the power of wind generation at time t, $P_{\text{p}}(t)$ is the power of photovoltaic generation at time t, $P_{\text{L}}(t)$ is the power of load at time t.

(2) Loss rate of power supply

The loss rate of power supply is used to indicate the ability of WPS-HPS to provide load demand [9], which is defined as

$$f = \frac{\sum_{t=1}^{24}\left[P_{L}(t) - \left(P_{\text{w}}(t) + P_{\text{p}}(t) + P_{\text{m}}(t)\right)\right]}{\sum_{t=1}^{24} P_{L}(t)} \tag{9}$$

Where $P_{\text{m}}(t)$ is the power of GESS at time t.

(3) Contribution rate of wind and photovoltaic

The contribution rate of wind-photovoltaic hybrid power system is reflected by the ratio of the power provided to the load by wind and photovoltaic, which is defined as

$$R = \frac{\sum_{t=1}^{24} E(t)}{\sum_{t=1}^{24} P_{L}(t)} \tag{10}$$

When $P_{\text{w}}(t) + P_{\text{p}}(t) \geq P_{L}(t)$,

$$E(t) = P_{L}(t) \tag{11}$$

When $P_{\text{w}}(t) + P_{\text{p}}(t) < P_{L}(t)$ and $P_{\text{m}}(t-1) = 0$,

$$E(t) = P_{\text{w}}(t) + P_{\text{p}}(t) \tag{12}$$

When $P_{\text{w}}(t) + P_{\text{p}}(t) < P_{L}(t) < P_{\text{w}}(t) + P_{\text{p}}(t) + P_{\text{m}}(t-1)$ and $P_{\text{m}}(t-1) > 0$,

$$E(t) = P_{L}(t) \tag{13}$$

When $P_{L}(t) \geq P_{\text{w}}(t) + P_{\text{p}}(t) + P_{\text{m}}(t-1)$ and $P_{\text{m}}(t-1) > 0$,

$$E(t) = P_{\text{w}}(t) + P_{\text{p}}(t) + P_{\text{m}}(t-1) \tag{14}$$

Where $E(t)$ is the power provided to the load by wind and photovoltaic at time t.

3.2 Objective function

The objective function of this paper is that the total cost of WPS-HPS is the smallest, which is defined as

$$\min F_1 = \min\left(C_1 + C_2 - C_3 + C_4\right) \tag{15}$$

Where C_1 is initial cost of each part, C_2 is operation and maintenance cost of each part, C_3 is sales cost of the system, C_4 is cost of electricity purchased by the system.

The cost of each part is defined as

$$C_1 = N_{\text{w}}\cdot C_{\text{w1}} + P_{\text{p}}\cdot C_{\text{p1}} + C_{\text{m1}} \tag{16}$$

$$C_2 = \Delta t_{\text{w}}\cdot C_{\text{w2}} + \Delta t_{\text{p}}\cdot C_{\text{p2}} + \Delta t_{\text{m}}\cdot C_{\text{m2}} \tag{17}$$

$$C_3 = C_i(t)\cdot\Delta E_1 + C_j(t)\cdot\Delta E_2 \tag{18}$$

$$C_4 = C_i(t)\cdot\Delta E_3 \tag{19}$$

Where N_{w} is installed number of WF, P_{p} is capacity of PVPS, C_{w1} is unit price of draught fan, C_{p1} is unit price of PVPS capacity, C_{m1} is cost of GESS. Δt_{w}, Δt_{p} and Δt_{m} are the running time of WF, PVPS and GESS, respectively. C_{w2}, C_{p2} and C_{m2} are the unit operation and maintenance cost of WF, PVPS and GESS, respectively. $C_i(t)$ is electricity price of power grid at time t, $C_j(t)$ is the price of electricity sold by the system at time t, ΔE_1 is the amount of electricity that the system sells to power grid at time t, ΔE_2 is the amount of electricity that the system provides to the load at time t, ΔE_3 is the amount of electricity purchased by the system from power grid.

3.3 Constraint condition

The installed number of WF, capacity of PVPS, capacity of GESS and evaluation index are restricted.

$$0 \le N_{\mathrm{w}} \le N_{\mathrm{r\,max}} \tag{20}$$

$$0 \le P_{\mathrm{p}} \le P_{\mathrm{pmax}} \tag{21}$$

$$0 \le P_{\mathrm{m}} \le P_{\mathrm{mmax}} \tag{22}$$

$$0 \le N_{\mathrm{w}} \cdot P_r + P_{\mathrm{p}} \le 0.3 \cdot \sum_{t=1}^{24} P_L(t) \tag{23}$$

$$D \le D_{\mathrm{r}} \tag{24}$$

$$f \le f_{\mathrm{r}} \tag{25}$$

$$R \le R_{\mathrm{r}} \tag{26}$$

Where $N_{\mathrm{r\,max}}$ is the maximum installed number of WF, P_{pmax} is the maximum capacity of PVPS, P_{mmax} is the maximum capacity of GESS, D_{r} is the reference value when the system utilizes the complementary features of wind and photovoltaic, f_{r} is the loss rate of power supply allowed by load within a tolerance range, R_{r} is the reference value for the contribution rate of wind and photovoltaic.

3.4 System capacity optimization configuration strategy

The WPS-HPS is connected to power grid. When the wind and photovoltaic generation are sufficient, energy storage system charges. After the rated capacity is filled, there is still surplus and then fed into power grid.

$$P(t)=P_{\mathrm{w}}(t)+P_{\mathrm{p}}(t)-P_{\mathrm{m}}(t)-P_{\mathrm{L}}(t) \tag{27}$$

When the wind and photovoltaic generation are insufficient, energy storage system discharges. And if the load demand is not met, it purchases electricity from power grid.

$$P_{\mathrm{d}}(t)=P_{\mathrm{L}}(t)-\left(P_{\mathrm{w}}(t)+P_{\mathrm{p}}(t)+P_{\mathrm{m}}(t)\right) \tag{28}$$

In this paper, the objective function is that the total cost of WPS-HPS is the smallest, and the capacity of WF, PVPS and GESS are taken as optimization variables to solve the optimal capacity configuration. The cat swarm optimization [10] is used to solve the capacity optimization configuration model of WPS-HPS.

4. SIMULATION ANALYSIS

4.1 Scene selection

This paper selects a region in Gansu Province, China as the reference area. The latitude of this area is $35°22'$ and the longitude is $105°1'$. According to the national meteorological information center, average illumination of this area is $4.32\mathrm{kW/m^2}$ and monthly average wind speed is shown in Table 1. Reference [11] gives the load of one day in this area. In this paper, the rated wind speed of the fan is $11\mathrm{m/s}$, the cut-in wind speed is $3\mathrm{m/s}$, the cut-out wind speed is $20\mathrm{m/s}$ [12]. The operating temperature of the panel is $25°\mathrm{C}$, the reference temperature is $25°\mathrm{C}$, the temperature coefficient of power is 1 and the illumination under standard text conditions is $1\mathrm{kW/m^2}$ [13]. The weight of GESS is 10000 tons, the slope is $30°$ and the gravitational acceleration is $9.8\mathrm{m/s^2}$.

Table 1 Monthly average wind speed

month	1	2	3	4	5	6
wind speed (m/s)	4.1	4.5	5.1	5.6	5.6	5.1
month	7	8	9	10	11	12
wind speed (m/s)	5.0	5.2	4.9	4.7	4.4	4.2

Annual wind speed prediction data and illumination prediction data of the region can be obtained in the HOMER software [14], as shown in Fig 3 and Fig 4. We select the wind speed and illumination on a representative day.

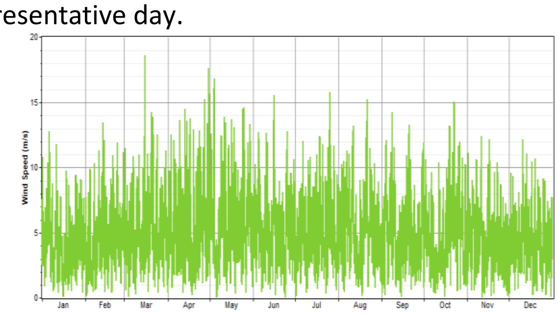

Fig 3 Annual wind speed in the area

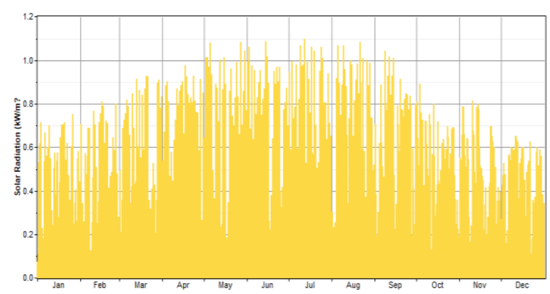

Fig 4 Annual illumination in the area

The initial cost and operation and maintenance cost of WF, PVPS and GESS are shown in Table 4 [13].

Table 4 Installation cost and operation and maintenance cost of each distributed generation

	installation cost($/each fan)	operation and maintenance($/day)
WF	31050	44
	installation cost($/kW)	operation and maintenance($/day)
PVPS	916	34

	installation cost($/kW)	operation and maintenance($/day)
GESS	547	22

4.2 Simulation results

The energy storage system capacity is determined by the height of mountain in this paper. The height of 100m, 200m, 300m and 400m are selected for simulation analysis.

(1) Configuration 1

When the height of mountain is 100m, the evaluation index is shown in Table 5, and the daily power curve is shown in Fig 5.

Table 5 Value of evaluation indicators and capacity

WF	PVPS	GESS
101	4109kW	647kW
D	*f*	*R*
0.4718	0.0998	0.7281
initial cost($)	operation and maintenance Cost($)	income($)
7251693	1675	1026

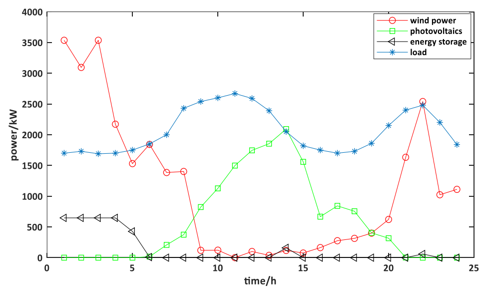

Fig 5 The daily power curve

(2) Configuration 2

When the height of mountain is 200m, the evaluation index is shown in Table 6, and the daily power curve is shown in Fig 6.

Table 6 Value of evaluation indicators and capacity

WF	PVPS	GESS
86	4087kW	1327kW
D	*f*	*R*
0.4517	0.1088	0.7046
initial cost($)	operation and maintenance Cost($)	income($)
7137833	1675	554

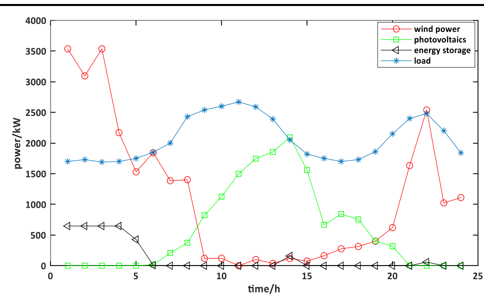

Fig 6 The daily power curve

(3) Configuration 3

When the height of mountain is 300m, the evaluation index is shown in Table 7, and the daily power curve is shown in Fig 7.

Table 7 Value of evaluation indicators and capacity

WF	PVPS	GESS
87	3608kW	2008kW
D	*f*	*R*
0.4803	0.0542	0.6877
initial cost($)	operation and maintenance Cost($)	income($)
7102696	1675	205

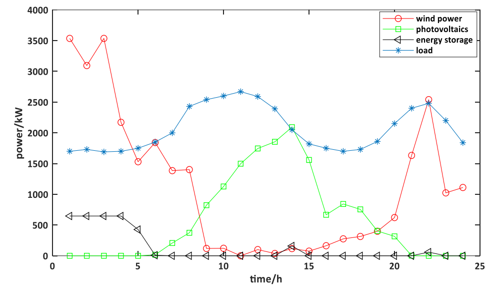

Fig 7 The daily power curve

(4) Configuration 4

When the height of mountain is 400m, the evaluation index is shown in Table 8, and the daily power curve is shown in Fig 8.

Table 8 Value of evaluation indicators and capacity

WF	PVPS	GESS
87	4114kW	2688kW
D	*f*	*R*
0.4506	0.1617	0.6861
initial cost($)	operation and maintenance Cost($)	income($)
7937951	1675	359

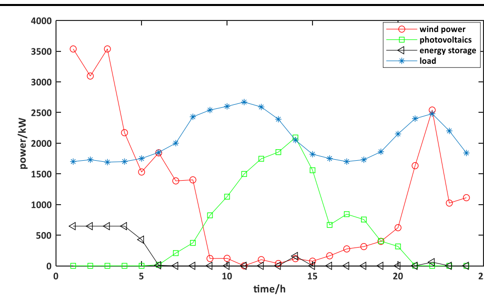

Fig 8 The daily power curve

The three indicators under different configurations are compared. The comparison curve of indicators is shown in Fig 9. Only in terms of the complementary features of wind and photovoltaic, *D* of configuration 3 is the largest and *D* of configuration 2 and 4 is relatively small. Therefore, configuration 2 and 4 are better. Only in terms of the loss rate of power supply, *f* of configuration 3 is the smallest and *f* of configuration 4 is the largest. Therefore, configuration 3 is better. Only in terms of the contribution rate of wind and photovoltaic, *R* of configuration 1 is the largest and *R* of configuration 3 and 4 are the smallest. Therefore, configuration 1 is better. In terms of initial cost and daily income, initial cost of configuration 4 is the highest and daily income of configuration 1 is the highest. If the average daily income is that day's income, configuration 1 can recover the cost as quickly as possible. By analyzing each indicator, initial cost and income, it can be seen that configuration 1 is better.

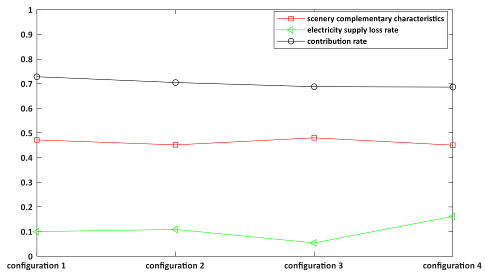

Fig 9 Three indicators under different configurations

5. CONCLUSIONS

In order to support solving the problem of abandoned wind power and solar, this paper proposed a WPS-HPS model based on gravity energy storage technology. The main conclusions are summarized as follows:

(1) This paper proposes three indicators: the complementary features of wind and photovoltaic, the loss rate of power supply and the contribution rate of wind and photovoltaic. The indicators can better evaluate the WPS-HPS.

(2) The simulation results show that the proposed capacity optimization configuration method is reasonable and effective.

(3) Most of the northwestern regions have high altitudes and most of them are mountainous areas in China. GESS depends on the mountain, so there is a natural advantage of the mountain in the northwest. Its promotion in renewable energy power generation can effectively improve energy utilization density and improve the capacity of wind power and photovoltaic power generation.

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