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Investigation on Equivalent Trans-utilization Mode and Benefit of Wind Energy

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ABSTRACT

For economic benefit of wind power generation, the equivalent conversion relationships and models between the different “quality” energy are studied deeply in the conversion processes of wind energy. Considering the effect of load demand characteristics and energy supply price on the wind energy utilization mode comprehensively, the multi-objective trans-utilization optimization model of wind energy is established, which the objections are both the maximum wind energy utilization ratio and comprehensive operational benefit of the energy consumption systems. Then, the quantum-behaved particle swarm optimization method is used to solve the model. By contrast to the traditional unitary energy supply mode, the results showed that the proposed models can improve the wind energy comprehensive utilization rate, and increase energy selling benefit of the energy supply system. The rationality and superiority of models are verified, and that provides a new idea for the large-scale develop and utilize wind energy.

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1. INTRODUCTION

As a typical of renewable energy, the wind energy has become an important component of the current energy structure and a great development direction of energy resources in the future. However, with the development of wind power integration on power system, the problems of curtailed wind have become more and more standouts, that causes great losses to the exploitation and utilization of wind energy. So, the developers take a wait-and-see attitude to the developmental prospects of the wind energy resources [1, 2].

Because the development and utilization of wind energy are affected by the environmental factors, so, from the wind energy itself point of view, it exhibits the extremely strong characteristic of intermittence and fluctuation. The inverse load distribution characteristics increase the difficulty of utilization and consumption of wind energy resources [3]. From the regional distribution point of view, the wind energy resources is usually far away from the power load center, and the local power load does not have the capacity of large-scale wind energy utilization [4]. The export power transmission of wind energy is an efficient approach to solve the accommodation problem of large-scale wind energy. But, that is restricted by transmission capacity, transmission power stability, electric load demand, and other multiple factors. Based on the flexible electricity price, AI Xin et al. [5] construct the chance-constrained model of wind power accommodation to verify the effectiveness of demand side response to the wind power accommodation. In order to improve the utilization ratio and containing capability of wind power, Yu Dayang et al. [6] propose the coordination scheduling model for the wind power and electric vehicle by binding the charge-discharge load properties of electric vehicle. The multiple energy storage techniques are used by Zhen Le [7] to transfer the wind energy by the different energy forms to improve the comprehensive utilization ratio of wind energy. Also, the power balance control strategy between the wind energy and energy storage system is studied by Wu Xiong et al. [8, 9] to ensure safe and stable operation of energy supply system.

From the above, the transformation, utilization and transmission of wind energy are realized mainly by means of the single electric energy form. However, there

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are cooling, heating, power and other forms load demands in the load area. Thus, on the basis of the conception of global energy interconnection, the equivalent trans-utilization models are constructed by analyzing the multiple transforming relationship of energy in the wind energy utilization progress. Considering the influence of energy supply price on energy utilization types comprehensively, the multi-objective optimization model of wind energy is established which the objections are both the maximum wind energy utilization ratio and comprehensive operational benefit of the energy consumption systems. Then, the best utilization strategies of wind energy are given in the different periods by solving the models. Through comparing the examples in the different seasons, the results showed that the proposed models can improve the wind energy comprehensive utilization rate, and increase comprehensive benefit of wind energy utilization. That provides a new idea for the large-scale wind energy development and utilization in the future.

2. EQUIVALENT TRANS-UTILIZATION MECHANISM OF WIND ENERGY RESOURCE

Wind energy is the important component of the current energy structure, and transformation and utilization of wind energy need to experience the multiple transformation process of energy to satisfy the diversity load demand. In order to decrease the inverse load characteristics, the wind energy can be transferred in the time sequence to satisfy the diversity load demands and increase the comprehensive utilization ratio of wind energy. This paper analyzes the wind energy utilization mode in the transformation and utilization angles.

2. 1. Equivalent Trans-utilization Characteristics of Energy The utilization process of wind energy is a sophisticated energy transformation and transmission process. The utilization forms of energy are decided by the energy demand forms in the load area. In the whole utilization process, because of the difference of the ‘exergy’ of energy, for the different energy, there are various cascade transformation utilization characteristics. Based on the background of the global energy interconnection, the original and single energy supply structure are changed to the multilayer and graphic formula structure. The multilayer trans-utilization relationship of wind energy can be expressed as:

2. 1. 1. Energy Trans-utilization Model from Wind Energy Form to Electric Energy Form The wind power generation progress is that the part of the wind energy is transferred into the electric energy. Therefore, the output of electric energy is effected mainly by the wind speed. The wind energy trans-utilization model can be expressed as follows [10]:

$$P_{\mathrm{wt}}=\begin{cases}0 & v\le v_{\mathrm{ci}}\\ k_1\cdot v+k_2 & v_{\mathrm{ci}}<v<v_{\mathrm{r}}\\ P_{\mathrm{wt,0}} & v_{\mathrm{r}}\le v<v_{\mathrm{co}}\\ 0 & v\ge v_{\mathrm{co}}\end{cases}\tag{1}$$

there, $k_1=P_{\mathrm{wt,0}}/(v_{\mathrm{r}}^3-v_{\mathrm{ci}}^3)$, $k_2=k_1 \cdot v_{\mathrm{ci}}^3$. $P_{\mathrm{wt,0}}$ is the rated power of wind turbine. v_{ci} and v_{co} are the cut-in and cut-out wind speed respectively. Furthermore, v_{r} and v are the rated and actual wind speed. Thus, the actual wind speed v will change between the 0 m/s and cut-out wind speed, and that results in the uncertainty and interference to the power system.

2. 1. 2. Energy Trans-utilization Model from Eletric Enenrgy Form to Cooling Energy Form

The energy transformation progress from the electric energy form to cool energy form is a progress from the high quality energy form to low quality energy form, so the transformation coefficient of performance is higher. According to the running condition of the refrigeration system, the mathematical expression of electric consumption and cooling power and the coefficient of performance can be expressed as follows:

$$\begin{cases}P_{\mathrm{ce}}(t)=P_{\mathrm{ec}}(t)\cdot COP_{\mathrm{rc}}(t)\\ COP_{\mathrm{rc}}(t)=A_1+\dfrac{A_1-A_2}{1+e^{\frac{\overline{P_{\mathrm{ce}}(t)}-A_3}{w}}}\end{cases}\tag{2}$$

where, $P_{\mathrm{ce}}(t)$ is the cooling output power. $P_{\mathrm{ec}}(t)$ is the electric consumption for cooling power. $COP_{\mathrm{rc}}(t)$ is the transformation coefficient of performance. $P_{\mathrm{ce}}(t)$ is the amortized power of cooling power. A_i (i=0,1,2) and w are the fitting coefficient of transformation coefficient of performance.

2. 1. 3. Energy Trans-utilization Model from Electric Energy Form to Heating Energy Form

The transformation progress is also form the high quality energy to low quality energy form. But the transformation coefficient of performance is relative stability. The same, according to the running condition of the refrigeration system, the mathematical expression of electric consumption and heating power and the coefficient of performance can be expressed as follows [11]:

$$P_{\mathrm{he}}(t)=P_{\mathrm{eh}}(t)\cdot COP_{\mathrm{eb}}\tag{3}$$

where, the $P_{\mathrm{eh}}(t)$ and $P_{\mathrm{he}}(t)$ are the electric consumption and heating output power respectively. COP_{eb} is the transformation coefficient of performance.

2. 2. Time Sequence Metastasis Characteristics of Multi-energy Forms In term of the trans-utilization characteristics of energy, the transformation and utilization of wind energy resource are effected easily by the environmental factors, and the output of electric power does not vary with the fluctuation of load demands. So, in some time quantum, there is the great difference between the output of electric power and load demands. In order to satisfy the diversity load demand, the wind energy can be transferred in time sequence by the diversification energy storage system to improve the comprehensive utilization ratio of wind energy. when the wind energy is transferred by the electric energy form, the mathematical model can be expressed as Equation (4) [12]:

$$\begin{cases} E_{\mathrm{bt}}(t+1) = E_{\mathrm{bt}}(t)\cdot(1-\delta_{\mathrm{e}}) + P_{\mathrm{bt,in}}(t)\cdot\eta_{\mathrm{in}}\cdot\Delta t \\ E_{\mathrm{bt}}(t+1) = E_{\mathrm{bt}}(t)\cdot(1-\delta_{\mathrm{e}}) - P_{\mathrm{bt,out}}(t)\cdot\Delta t/\eta_{\mathrm{out}} \end{cases} \tag{4}$$

where, $E_{\mathrm{bt}}(t+1)$ is the stored energy of electric power storage system in time $(t+1)$. $E_{\mathrm{bt}}(t)$ is the stored energy in time t. δ_{e} is the self-discharge rate of electric power storage system. $P_{\mathrm{bt,in}}(t)$ and $P_{\mathrm{bt,out}}(t)$ are the operating power of electric power storage system in charging and discharging process respectively. η_{in} and η_{out} are the charge and discharge efficiency of electric power storage system. Δt is the unit time interval.

When the wind energy is transferred by the cool energy form, the mathematical model can be expressed as Equation (5) [13]:

$$\begin{cases} C_{\mathrm{cs}}(t+1) = C_{\mathrm{cs}}(t)\cdot(1-\sigma_{\mathrm{cs}})^{\Delta t} + P_{\mathrm{cs,in}}(t)\cdot\mu_{\mathrm{cs}}\cdot\Delta t \\ C_{\mathrm{cs}}(t+1) = C_{\mathrm{cs}}(t)\cdot(1-\sigma_{\mathrm{cs}})^{\Delta t} - P_{\mathrm{cs,out}}(t)\cdot\Delta t/\mu_{\mathrm{cs}} \end{cases} \tag{5}$$

where, $C_{\mathrm{cs}}(t+1)$ is the stored energy of cool storage system in time $(t+1)$. $C_{\mathrm{cs}}(t)$ is the stored energy in time t. σ_{sc} is the energy loss coefficient of cool storage system. $P_{\mathrm{sc,in}}(t)$ and $P_{\mathrm{sc,out}}(t)$ are the operating power of cool energy storage system in charging and discharging process respectively. μ_{cs} is the transfer coefficient of cool energy. When the wind energy is transferred by the heat energy form, the mathematical model can be expressed as Equation (6) [14]:

$$\begin{cases} H_{\mathrm{hs}}(t+1) = H_{\mathrm{hs}}(t)\cdot(1-\sigma_{\mathrm{hs}}) + P_{\mathrm{hs,in}}(t)\cdot\mu_{\mathrm{hs}}\cdot\Delta t \\ H_{\mathrm{hs}}(t+1) = H_{\mathrm{hs}}(t)\cdot(1-\sigma_{\mathrm{hs}}) - P_{\mathrm{hs,out}}(t)\cdot\Delta t/\mu_{\mathrm{hs}} \end{cases} \tag{6}$$

where, $H_{\mathrm{hs}}(t+1)$ is the stored energy of heat storage system in time $(t+1)$. $H_{\mathrm{hs}}(t)$ is the stored energy in time t. σ_{hs} is the energy loss coefficient of heat storage system. $P_{\mathrm{hs,in}}(t)$ and $P_{\mathrm{hs,out}}(t)$ are the operating power of heat energy storage system in charging and discharging process respectively. μ_{hs} is the energy conversion efficiency of heat storage system.

3. OPTIMIZATION MODEL OF WIND POWER UTILIZATION

3. 1. Objective Function

3. 1. 1. Maximum Utilization Model of Wind Energy The utilization ratio of wind energy is that the ratio of current available wind energy to the current maximum wind energy resource supply.

$$\begin{cases} f_1 = \max(\eta) \\ \eta = \dfrac{\sum_{t=1}^{T} P_{\mathrm{wt}}(t)\cdot\Delta t}{\sum_{t=1}^{T} E_{\mathrm{wt}}(t)} \end{cases} \tag{7}$$

where, T is the number of time intervals in an execution cycle. $P_{\mathrm{wt}}(t)$ is the output power of wind generation in time t. $E_{\mathrm{wt}}(t)$ is the current maximum wind energy resource supply.

3. 1. 2. Maximum Operating Benefit of Energy Supply Supply System The operating benefit of energy supply system is the economic benefit of the elecetirc, cooling and heating energy supply.

$$f_2 = \max\left(C_{\mathrm{powr}} + C_{\mathrm{cooling}} + C_{\mathrm{heating}} - C_{\mathrm{operation}}\right) \tag{8}$$

$$\begin{aligned} C_{\mathrm{power}} &= \sum_{t=1}^{T} P_{\mathrm{power}}(t)\cdot c_{\mathrm{power}}(t)\cdot\Delta t \\ C_{\mathrm{cooling}} &= \sum_{t=1}^{T} P_{\mathrm{ce}}(t)\cdot c_{\mathrm{cooling}}(t)\cdot\Delta t \\ C_{\mathrm{heating}} &= \sum_{t=1}^{T} P_{\mathrm{he}}(t)\cdot c_{\mathrm{heating}}(t)\cdot\Delta t \end{aligned} \tag{9}$$

$$\begin{aligned} C_{\mathrm{operation}} = {} & \sum_{t=1}^{T} P_{\mathrm{wt}}(t)\cdot c_{\mathrm{wt}}\cdot\Delta t + \sum_{t=1}^{T} P_{\mathrm{ce}}(t)\cdot c_{\mathrm{rc}}\cdot\Delta t \\ & + \sum_{t=1}^{T} P_{\mathrm{he}}(t)\cdot c_{\mathrm{eb}}\cdot\Delta t + \sum_{t=1}^{T}\sum_{i=1}^{n} \left|P_i(t)\right|\cdot c_i\cdot\Delta t \end{aligned} \tag{10}$$

where, the C_{power}, C_{cooling}, C_{heating} and $C_{\mathrm{operaiton}}$ are the economic benefit of electric power, cooling, heating energy supply and comprehension operation cost of energy supply system in an operation cycle, respectively. $P_{\mathrm{power}}(t)$, $P_{\mathrm{cooling}}(t)$ and $P_{\mathrm{heating}}(t)$ are the output power of electric, cooling and heating. $c_{\mathrm{power}}(t)$, $c_{\mathrm{cooling}}(t)$ and $c_{\mathrm{heating}}(t)$ are the supply price of electric, cool and heat energy. $P_i(t)$ is the operation power of the type-i energy storage system. c_{wt}, c_{rc}, c_{eb} and c_i are operation cost of wind generation, refrigerating machine, electric boiler and energy storage system.

3. 2. Constraint Condition of Energy Supply System

$$0 \le P_{\mathrm{wt}}(t) \le P_{\mathrm{wt,forecast}}(t) \tag{11}$$

where, $P_{\mathrm{wt,forecast}}(t)$ is the maximum output power of wind generation in the time t.

$$0 \le P_{\mathrm{ce}}(t) \le P_{\mathrm{ce}}^{\max}(t) \tag{12}$$

where, $P_{\mathrm{ce}}^{\max}$ is the maximum cooling power of refrigeration machine in the time t.

$$0 \le P_{\mathrm{he}}(t) \le P_{\mathrm{he}}^{\max}(t) \tag{13}$$

where, $P_{he}^{max}(t)$ is the maximum heating power of electric boiler in the time t.

$$\begin{cases} P_i^{min}(t) \le P_i(t) \le P_i^{max}(t) \\ \sum_{t=1}^{T} P_i(t) = 0 \end{cases} \tag{14}$$

where, $P_i^{min}(t)$ and $P_i^{max}(t)$ are the minimum and maximum operation power of type-i energy storage system.

$$\begin{aligned} &P_{power}(t) + P_{bt,out}(t) \le P_{PL}(t) \\ &P_{ec}(t) + P_{cs,out}(t) \le P_{CL}(t) \\ &P_{hc}(t) + P_{hs,out}(t) \le P_{HL}(t) \end{aligned} \tag{15}$$

$$E_{power}(t) + E_{cooling}(t) + E_{heating}(t) = E_{wt}(t) \tag{16}$$

where, the $P_{PL}(t)$, $P_{CL}(t)$ and $P_{HL}(t)$ are the power, cooling and heating load demands respectively in the time t. $E_{power}(t)$, $E_{cooling}(t)$ and $E_{heating}(t)$ are the energy consumption for power, cooling and heating.

4. CASES ANALYSIS

4. 1. Case Example

In order to confirm the validity of the proposed methods and model, the practical calculation example is used to verify the effectiveness of that. The system structure diagram is shown in Figure 1. Where, the installed capacity of wind generation is 200kW. The maximum cooling power of refrigeration machine is 300 kW. The maximum heating power of electric boiler is 200 kW. The maximum operation power of electric and cool storage system is 100 kW. The maximum operation power of heat storage system is 50 kW. The operation period of energy supply system is one day. The time-of-out (TOU) power price is used for the supply price of electric power and shown in Table 1. Where, the peak periods are 08:00-12:00, 15:00-16:00 and 19:00-22:00. The off-peak periods are the 00:00-06:00 and 23:00-24:00, and the ordinary periods are 07:00-08:00, 13:00-14:00 and 17:00-18:00.

4. 2. Comparative Analysis

4. 2. 1. In Summer

The running condition of electric power storage in single power supply mode is shown as Figure 2. When the wind energy is only used to satisfy the power load demand in a period, the power load demands are met in 50% of the operation period, and the utilization ratio of wind energy is 70.05%. If the excess wind energy is stored by the electric power storage system and used when necessary, the utilization ratio of wind energy can reach to 86.47%. The running condition of electric power storage is shown in Figure 3. When the wind energy is only used for satisfying the cooling load demand, the transformation progress is from the high quality energy form to low quality energy form. So, the transformation ratio is higher, and the wind energy can meet the cooling load demand in all of operation period. But the utilization ratio of wind energy is only 44.95% which is far lower than that used for the electric power load demand. In summer, the wind energy utilization comparison in different utilization forms is shown in Figure 4.

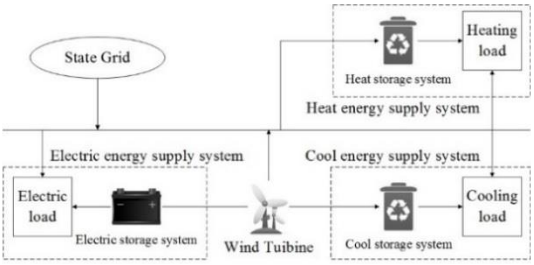

Figure 1. System structure

TABLE 1. Time-of-out (TOU) power price

Time Interval	Price（￥/ kW·h）
peak periods	0.76
off-peak periods	0.51
ordinary periods	0.26

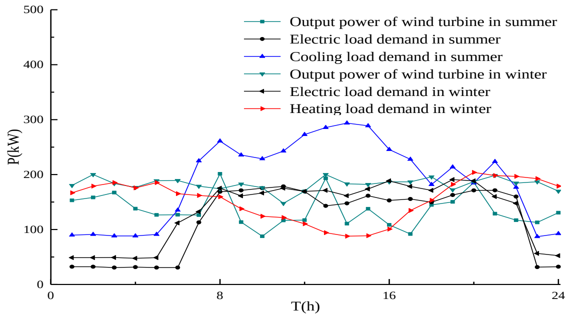

Figure 2. Forecast of the output power of wind turbine and load in a typical day in different seasons

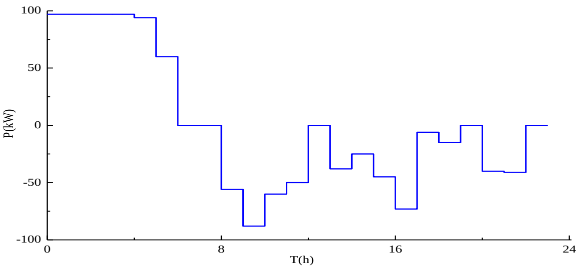

Figure 3. Running condition of electric power storage in single power supply mode

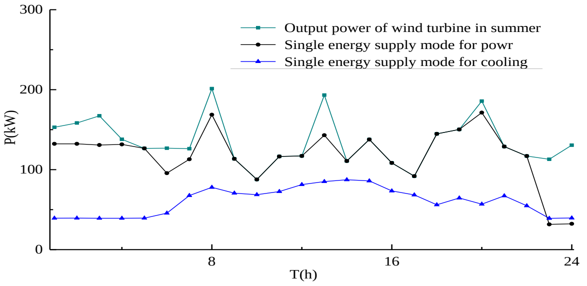

Figure 4. Wind energy utilization comparison using single energy supply mode in a typical day in summer

For the convenience of calculation, the transaction value of cool energy is also based on consumption price (0.2￥/kWh). Thus, in the 08:00-22:00, the wind energy will satisfy the electric power load demand firstly to get the more economic benefit. Then, the excess wind energy is used for the cooling load demand. The same, in the 23:00-07:00, the wind energy will satisfy the cooling load demand firstly, and the excess wind energy is used to meet the electric power load demand. After that, if there is also the excess wind energy, based on the guidance function of energy supply price mechanism, it will be transferred and used again in future by means of the electric or cool energy form.Running condition of energy storage systems is shown in Figure 5. In the whole operation period, 17.23% of wind energy is transferred in form of electric power energy, and 1.92% of wind energy is in form of cool energy. Energy supply characteristics of wind energy is shown in Figure 6. Where, 13.58% of wind energy is used for supplying the cooling load energy. Because there is the energy loss in the energy conversion processes, the comprehension utilization ratio of wind energy is 98.36%.

In summer, the amount transfer, comprehension utilization ratio and economical returns of wind energy are shown in Table 2. From that, it is shown that compared with single energy supply modes, mixed power supply mode can make the system further improve the utilization of wind energy, and get the more economic benefits.

4. 2. 2. In Winter Combined with Figure 2, wind energy resources in winter is more than that in summer. When the system takes the single energy supply mode, that is the wind is only used to satisfying the heating load demand, the wind energy can just satisfy the heating load demand in 75% of the operation period. The same, if the excess wind energy is stored by the heat storage system and used when necessary, the utilization ratio of wind energy can reach to the 84.68%. The running condition of electric power storage is shown in Figure 7.

When the wind energy is only used for satisfying the electric power load demand, the electric power load demands are met in 50% of the operation period, and the utilization ratio of wind energy is 71.32%. By virtue of heat energy storage, the wind energy can meet the electric power load demand in the whole operation period. But the utilization ratio of wind energy could only reach to 74.62%. In winter, the wind energy utilization comparison in different utilization forms is shown in Figure 8.

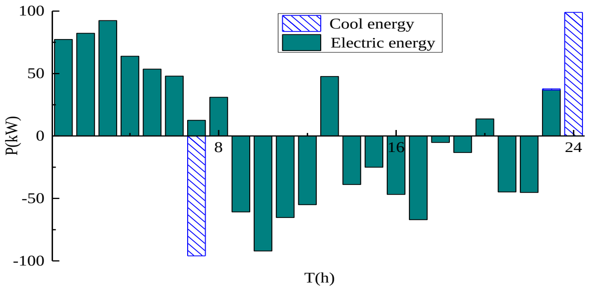

Figure 5. Running condition of energy storage systems in a typical day in summer

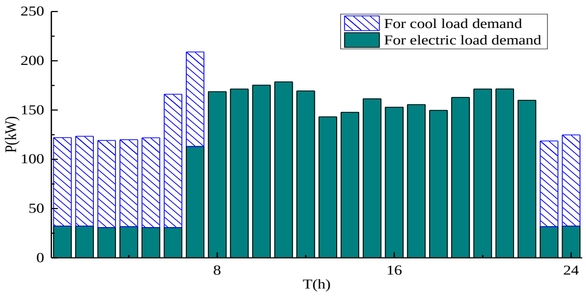

Figure 6. Energy supply characteristics of wind energy in a typical day in summer

TABLE 2. Wind energy utilization comparison using different energy supply mode in summer

	Amount Transfer (kW·h)	**Utilization Ratio (%)**	**Economic Income (￥)**
single power mode	532.61	86.47	1493.16
single cooling mode	0	44.95	613.25
mixed supply mode	660.15	98.36	1618.80

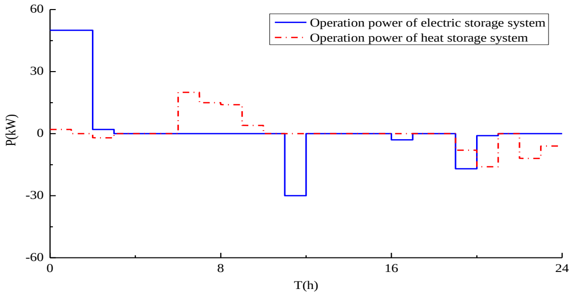

Figure 7. Running condition of heat storage system in single power supply mode

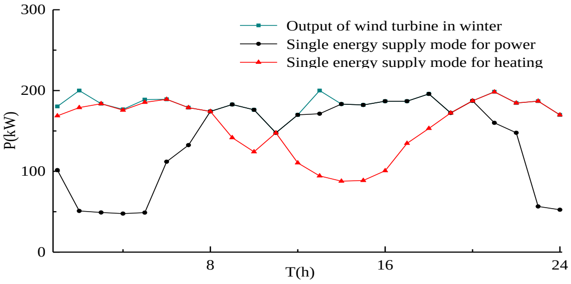

Figure 8. Wind energy utilization comparison using single energy supply mode in a typical day in winter

For the convenience of calculation, the transaction value of heat energy is also based on consumption price (0.25 ¥/kWh). So, when the system takes the mixed energy supply mode, in the 23:00-06:00, the wind energy will satisfy the heating load demand firstly to get the more economic benefit. Then, the excess wind energy is used for the electric power load demand. In other time, the wind energy will supply the electric power load demand, and the excess wind energy is used for the heating load demand. After that, if there is also the excess wind energy, based on the guidance function of energy supply price mechanism, it will be transferred and used again in future by means of the electric or heat energy form. Running condition of energy storage systems is shown in Figure 9. In winter, the amount transfer, comprehension utilization ratio and economical returns of wind energy are shown in Table 3. From that, it is shown that compared with single energy supply modes, the mixed power supply mode can make comprehension utilization ratio of wind energy maximum, and get more economic benefits.

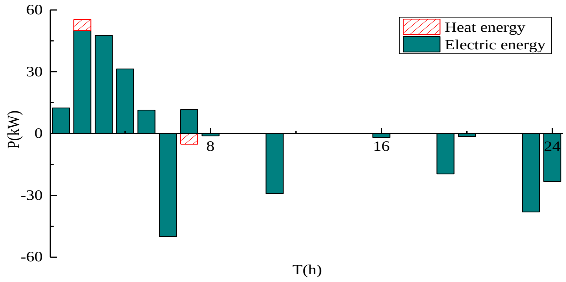

Figure 9. Operating condition of energy storage systemin a typical day in winter

TABLE 3. Wind energy utilization comparison using different energy supply mode in winter

	Amount Transfer (kW·h)	Utilization Ratio (%)	Economic Income (￥)
single power mode	52.02	74.62	1614.15
single cooling mode	57.95	84.68	509.99
mixed supply mode	169.90	99.61	1784.45

5. CONCLUSION

In this paper, though analyzing the equivalent conversion relationships between the different "quality" energy, the equivalent trans-utilization models of wind energy are constructed to make the comprehension utilization ratio of wind energy maximum and get the more economic benefits. Based on comprehensive consideration of the load demand characteristics and guidance function of energy supply price mechanism, both of the wind energy utilization ratio and comprehensive operational benefit of the energy consumption systems are fixed as the multi-objective optimization model. Then, though solving the model by the quantum-behaved particle swarm optimization method, best operation scheme is proposed. By contrast with the single energy supply modes, the result is shown that according to the diversification load demands, trans-utilization mode of wind energy resources can be changed to improve the comprehension utilization ratio of wind energy maximum and get the more economic benefits. That provides a new idea for development and utilization of large-scale wind power.

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Investigation on Equivalent Trans-utilization Mode and Benefit of Wind Energy

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چکیده

برای به دست آوردن مزیت اقتصادی تولید انرژی باد، روابط تبدیل مدل معادل بین انرژی "کیفیت" متفاوت در فرایندهای تبدیل انرژی باد مورد بررسی قرار می‌گیرد. با توجه به تأثیر ویژگی‌های تقاضا و قیمت عرضه انرژی در حالت استفاده از انرژی باد، به طور جامع، مدل بهینه‌سازی چند منظوره انرژی باد تولید شده است که اعتراضات هر دو نسبت حداکثر استفاده از انرژی باد و مزایای بهره‌برداری جامع سیستم‌های مصرف انرژی است. سپس، برای حل مدل، روش بهینه‌سازی ذرات رفتار شده توسط کوانتومی مورد استفاده قرار می‌گیرد. بر خلاف حالت سنتی انرژی یکپارچه، نتایج نشان داد که مدل‌های پیشنهادی می‌توانند میزان بهره‌برداری جامع از انرژی باد را افزایش دهند و مزایای فروش انرژی در سیستم تامین انرژی را افزایش دهند. عقلانیت و برتری مدل‌ها تأیید شده است و این ایده جدید برای توسعه و استفاده از انرژی باد است.

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