Basic structure and mathematical model of integrated energy system in ecological park

Qianqian Song, Yongfu Liu*, Limei Zhang, Tongxu Yang and Linteng Zhen
Hebei Key Laboratory of Agricultural Big Data, Hebei Agricultural University, Baoding, China

*Corresponding author e-mail: lyfworld@hebau.edu.cn

Abstract. The ecological parks are rich in available resources and have various types of energy. The reasonable utilization of the available resources in the park can promote the healthy development of the park. This paper analysed the wind and solar energy resources and their output in the ecological park, and gave mathematical models of typical energy production, conversion, and storage equipment. According to the energy consumption characteristics of the park, the ecological parks were classified based on the characteristics of wind and solar power generation, and the basic structure of the integrated energy system of the ecological park was given.

1. Introduction
The ecological park has the characteristics of clean and green, energy saving and emission reduction, and has great potential in the consumption of new energy. In line with the concept of “layout for a green economy, innovation-driven development”, China has provided strong support for the construction of ecological parks. Energy Internet has become an inevitable trend to solve the problem of local consumption of distributed renewable energy, realizes the close integration of multiple energy networks, and improves the overall energy efficiency of the system [1]. The comprehensive utilization of energy in the ecological park is an application form of the energy Internet, which can realize energy complementation and cascade utilization. As the ecological park has diversified energy demand, the comprehensive energy system of the ecological parks should be researched to give full play to the complementary advantages of electricity, gas, heat and cold, which will help increase the penetration rate of renewable energy, increase energy efficiency, and promote energy sustainable development.

2. Analysis of wind and solar energy resources and their output characteristics in ecological park

2.1. Analysis of wind and solar energy resources in ecological park
Wind energy and solar energy, as the more commonly used new energy sources that can be used to generate electricity, are an important part of the energy supply unit of the ecological park. The quality of the wind and solar resources in the geographical location of the park will have a certain impact on the energy supply of the park.
2.1.1. Solar Energy Resources. Generally, the total amount of solar radiation in a region throughout the year is used as the criterion for judging the quality of a region's solar energy resources. According to the evaluation standard of solar energy resource abundance level [2]: The area where the total amount of solar radiation in a certain year is greater than or equal to 6300MJ/m$^2$ is called the most-abundant resource area; the area where the total amount of solar radiation in a certain year is in the range from 5040 to 6300MJ/m$^2$ is called the better-abundant resource area; the total amount of solar radiation in a certain year the area in the range from 3780 to 5040MJ/m$^2$ is called the abundant-resource area; The area where the total solar radiation is less than 3780MJ/m$^2$ in a certain year is called the general-resource area.

The total annual radiation is in the most-abundant resource area, better-abundant resource area and abundant-resource area, which is regarded as an area rich in solar energy resources and has good solar energy utilization conditions. It is suitable to use photovoltaic power generation technology to convert solar energy into electrical energy for use in the park daily power supply.

2.1.2. Wind energy resources. Judging the size of wind energy resources in a region can be based on the following two indicators [3]: Effective wind energy density and annual effective wind speed cumulative hours. According to the indicators, the wind energy resource areas in China can be divided into four levels: wind energy resource rich area, wind energy resource richer area, wind energy resource usable area and wind energy resource poor area, as shown in Table 1.

| Classification                  | Rich area | Richer area | Available area | Poor area |
|---------------------------------|-----------|-------------|----------------|-----------|
| Effective wind power density(W/m$^2$) | >200      | 150~200    | <50~150        | <50       |
| Annual wind speed≥3m/s          | >5000     | <4000~5000 | <2000~4000     | <2000     |
| Accumulated hours (h)           |           |             |                |           |
| Annual wind speed≥6m/s          | >2200     | <1500~2200 | <350~150       | <350      |
| Accumulated hours (h)           |           |             |                |           |

2.2. Characteristics analysis wind-solar power generation model and their output

2.2.1. Photovoltaic power generation unit. Photovoltaic (PV) generation is a common distributed power generation unit. Connecting distributed PV to the power system is conducive to the full use of PV resources and can improve the economy of the system. However, because the output of PV cell modules is affected by factors such as solar radiation intensity and ambient temperature, its output is random and volatile.

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The stable power output of PV power generation unit can adopt the following model: it can be expressed as [4]:

$$P_{PV} = P_{STC} \frac{G_{ING}}{G_{STC}} \left[1 + k(T_e - T_r)\right]$$

(1)

Where $P_{PV}$ is the actual output power of the PV generation unit; $P_{STC}$ is the maximum output power of the PV generation unit; $G_{ING}$ is the actual solar radiation intensity; $G_{STC}$ is the irradiation intensity, $G_{STC} =1000 \text{ W/m}^2$; $k$ is the temperature coefficient of power; $T_e$ is the actual working temperature of the PV panel; $T_r$ is the reference temperature at the standard test temperature, $T_r =25^\circ\text{C}$. Due to the different latitudes, the light intensity has certain differences, so the geographical location of the parks, the local climate conditions, and the temperature will all have a certain impact on the output
of PV equipment. Fig. 1 shows the PV output on a typical day in a typical season in a certain place. It can be seen from the curve trend in the figure that in the early morning from 0:00 to 6:00 and the night time period from 19:00 to 0:00, the PV output value is 0 due to the absence of sunlight; during the daytime period from 7 to 19:00, the output of PV equipment first increases and then decreases with changes in the intensity of the sun, reaching its peak around 12 to 13 noon. It can be seen that PV output has a certain law.

![Figure 1. Typical daily PV output curve of each season](image)

### 2.2.2. Wind power generation unit

Wind turbine (WT) power generation is a typical distributed generation unit. The relationship between WT output $P_w$ and wind speed $v$ is shown in Fig. 2.

![Figure 2. Wind turbine v-P characteristic curve](image)

WT output is related to wind speed. In actual operation, when the wind speed $v$ is given, the determination of the output of the wind turbine is generally solved according to the formula (2) given below [5]:

$$P_w(v_t) = \begin{cases} 
0 & v_t \leq v_{ei} \text{ or } v_t \geq v_{eo} \\
\frac{P_e}{v_r - v_{ei}} & v_{ei} \leq v_t \leq v_r \\
\frac{P_e}{v_r - v_{co}} & v_r \leq v_t \leq v_{co} 
\end{cases} \quad (2)$$

Where $P_w(v_t)$ is the output power of the WT within a certain range of wind speed; $v_t$ is the wind speed at time $t$; $v_{ei}$ is the cut-in wind speed; $v_{co}$ is the cut-out wind speed; $v_r$ is the rated wind
speed; $P_o$ is the rated output power of the WT. The difference in topography in different regions will have a certain impact on the wind speed, and the wind speed in different seasons also has certain differences. Fig. 3 shows the wind turbine output on a typical day in a typical season. From the curve trend in the figure, it can be seen that the wind power output is more random than the PV power output, because the wind speed changes in various time periods of a day, a quarter, or even a year, and there is no rule to follow. In summary, the wind power output has a certain randomness and intermittence.

**Figure 3. Typical daily fan output curve of each season**

3. Equipment model of integrated energy system in ecological park

The integrated energy system can realize the cascade utilization of energy by scientifically dispatching multiple energy sources and achieve the effect of energy organic coordination. It is mainly composed of energy production unit, energy conversion unit and energy storage unit. This paper starts from two aspects of energy conversion and storage unit model.

3.1. Energy Conversion Unit

3.1.1. Gas turbine. Gas turbine (GT) is typical conversion equipment from gas to electric, which uses natural gas as fuel. It has the advantages of high thermal efficiency, low cost, high reliability, and small environmental impact [6, 7]. Its working mode can be expressed as:

$$Ee_{GT}^{out}(t) = Ee_{GT}^{in}(t)\eta_e^{GT} / Q_{LHV}$$

where $Ee_{GT}^{out}(t)$ is the electrical energy output of the GT at time t; $Ee_{GT}^{in}(t)$ is the amount of natural gas entering the GT at time t; $\eta_e^{GT}$ is the power conversion efficiency of the GT; $Q_{LHV}$ is the low calorific value of natural gas.

3.1.2. Gas boiler. Gas boiler (GB) is a typical heating equipment from gas to heat in traditional heating mode [8], its working mode can be expressed as:

$$Eh_{GB}^{out}(t) = Eh_{GB}^{in}(t)\eta_h^{GB} / Q_{LHV}$$

where $Eh_{GB}^{out}(t)$ is the heat output of the GB at time t; $Eh_{GB}^{in}(t)$ is the amount of natural gas entering the GB at time t; $\eta_h^{GB}$ is the heat energy conversion efficiency of the GB; $Q_{LHV}$ is the low calorific value of natural gas.
3.1.3. Electric boiler. Electric boiler (EB) is typical conversion equipment from electric to heat, its working mode can be expressed as:

\[ \text{E}_{\text{HE}}^{\text{out}}(t) = \text{E}_{\text{HE}}^{\text{in}}(t)\eta_{\text{EB}} \] (5)

Where \( \text{E}_{\text{HE}}^{\text{out}}(t) \) is the heat output of the EB at time \( t \); \( \text{E}_{\text{HE}}^{\text{in}}(t) \) is the electric energy entering the EB at time \( t \); \( \eta_{\text{EB}} \) is the thermal energy conversion efficiency of the EB.

3.1.4. Heat pump. A heat pump (HP) uses heat in the surrounding environment and a small amount of electrical energy to increase the environmental temperature, its working mode can be expressed as:

\[ \text{E}_{\text{HP}}^{\text{out}}(t) = \text{E}_{\text{HP}}^{\text{in}}(t)\eta_{\text{HP}} \] (6)

where \( \text{E}_{\text{HP}}^{\text{out}}(t) \) is the heat output of the HP at time \( t \); \( \text{E}_{\text{HP}}^{\text{in}}(t) \) is the electric energy entering the HP at time \( t \); \( \eta_{\text{HP}} \) is the thermal energy conversion efficiency of the HP.

3.1.5. Electric refrigerator. An electric refrigerator (ER) is a typical conversion device from electric to cool, its working mode can be expressed as:

\[ \text{E}_{\text{ER}}^{\text{out}}(t) = \text{E}_{\text{ER}}^{\text{in}}(t)\text{COP}_{\text{ER}} \] (7)

Where \( \text{E}_{\text{ER}}^{\text{out}}(t) \) is the cold energy output of the ER at time \( t \); \( \text{E}_{\text{ER}}^{\text{in}}(t) \) is the electric energy entering the ER at time \( t \); \( \text{COP}_{\text{ER}} \) is the cold energy conversion efficiency of the ER.

3.1.6. Absorption chiller. Absorption chiller (AC) is a kind of cooling system which uses heat instead of electricity to cool the environment, lithium bromide refrigeration is a typical example, and its working mode can be expressed as:

\[ \text{E}_{\text{AC}}^{\text{out}}(t) = \text{E}_{\text{AC}}^{\text{in}}(t)\text{COP}_{\text{AC}} \] (8)

Where \( \text{E}_{\text{AC}}^{\text{out}}(t) \) is the cold energy output of the AC at time \( t \); \( \text{E}_{\text{AC}}^{\text{in}}(t) \) is the heat energy entering the AC at time \( t \); \( \text{COP}_{\text{AC}} \) is the cold energy conversion efficiency of the AC.

3.1.7. P2G equipment. P2G (power to gas) is a device from electricity to gas that can indirectly reduce the use of fossil fuels for power generation. At the same time, a large amount of CO\(_2\) is consumed during operation, which has the effect of reducing carbon emissions. P2G can be used in conjunction with biogas plants, sewage treatment plants, and breeding farms, which conforms to the principle of energy recycling in the ecological park. Its working mode can be expressed as:

\[ \text{E}_{\text{P2G}}^{\text{out}}(t) = \text{E}_{\text{P2G}}^{\text{in}}(t)\eta_{\text{P2G}} \] (9)

Where \( \text{E}_{\text{P2G}}^{\text{out}}(t) \) is the heat output of the P2G device at time \( t \); \( \text{E}_{\text{P2G}}^{\text{in}}(t) \) is the electric energy entering the P2G device at time \( t \); \( \eta_{\text{P2G}} \) is the conversion efficiency from electricity to gas of the P2G.

3.2. Energy storage unit

Distributed energy is intermittent and random, and energy storage can play the role of smoothing peaks and suppressing valleys. Energy storage is an important means to balance and regulate energy in energy grid. The energy storage methods in this article are electricity storage (ES), heat storage (HS), and cold storage (CS). The expression [9] is:

\[ E_{\omega}(t) = E_{\omega}(t-1) \cdot (1 - \lambda_{\omega} \cdot \Delta t) + (E_{\omega}^{\text{ch}}(t) \cdot \eta_{\omega} - \frac{E_{\omega}^{\text{dis}}(t)}{\eta_{\omega}}) \times \Delta t \] (10)
where $\omega$ is the type of energy storage equipment, $\omega \in \{ES, HS, CS\}$; $E_\omega(t)$ is the electricity, gas, heat and cold energy stored by the energy storage device in the system at time $t$; $\lambda_\omega$ is the dissipation rate of energy storage equipment; $E_{\omega \text{ch}}(t)$ and $E_{\omega \text{dis}}(t)$ are the charging and discharging power of the energy storage device during $t$ period; $\eta_{\omega \text{ch}}$ and $\eta_{\omega \text{dis}}$ are the charging and discharging efficiency of energy storage device; $\Delta t$ is the charging and discharging time.

4. Classification of ecological parks based on the output of wind and solar energy

Based on the previous analysis of wind and solar resources in the parks and their output characteristics, the types of ecological parks can be divided into wind energy utilization type, solar energy utilization type and wind-solar energy complementary type.

4.1. Wind energy utilization park

Parks that are located in areas with rich wind energy resources and lack solar energy resources are called wind energy utilization parks. Taking advantage of local wind energy resources, wind turbines are selected as distributed power sources in the parks.

4.2. Solar energy utilization park

A park that is located in an area rich in solar energy resources and lacks wind energy resources is called a solar energy utilization park. Take advantage of the good local solar conditions and select PV equipment as the distributed power supply in the park.

4.3. Wind-solar energy complementary park

A park where the geographical location of the wind and solar resources are all within a rich to good range is called a wind-solar energy complementary park. According to the output characteristics of wind and solar energy in the previous article, although wind and solar energy output has a certain degree of randomness and interval [10], however, due to the lack of light at night and the PV equipment does not provide power, the output of the wind turbine can fill the gap in PV output to a certain extent.

Figure 4. Integrated energy system of typical ecological park

A typical ecological park integrated energy system is shown in Fig. 4, where distributed power sources choose wind power generation, PV generation, and simultaneous selection of wind and PV generation respectively correspond to wind energy utilization parks, solar energy utilization parks and wind-solar complementary parks. When the electricity produced by the wind and solar modules is
sufficient to meet the demand of the power load, the power supply of the power grid is not needed, the surplus energy can be converted into other types of energy through energy conversion equipment to meet other energy needs in the park or be sent to the storage device; when the power generated by the wind and solar components is insufficient, the grid power supply, other energy conversion equipment, and energy storage and discharge are used to meet the power load demand of the park during that period. The demand for other loads in the park is provided by the capacity of energy conversion equipment.

5. Conclusions
Based on output analysis of the wind and solar resources in the ecological park, this paper gave mathematical models of typical energy production, conversion and storage equipment. Combined with the energy consumption characteristics of the park, the ecological park was classified into three categories based on the characteristics of wind and solar power generation, and the basic structural form of the integrated energy system of the ecological park was constructed, which provided a good reference for the efficient utilization and optimal allocation of various energy resources in the integrated energy system in the ecological parks.

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