A Park-type energy local area network planning method considering multi-energy co-optimization

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Abstract. Energy Internet, which is regarded as the new generation energy utilization system, is an ideal solution to achieve sustainable development. In this paper, we propose a park-type Energy Local Area Network (ELAN) planning method for the planning and operation control of the ELAN. Firstly, we classify the park from its industrial structure and analyse the positioning of the park in terms of energy, environment, and load factors. Then, the physical planning architecture of the park-type ELAN is built. Subsequently, a planning method of park-type ELAN is proposed, which can incorporate the optimization problem of multi-energy cooperative scheduling into the planning model. Finally, the effectiveness of the proposed method is verified by performing calculations with a solid waste treatment park system.

1. Introduction
As mankind moves into the industrial society, the demand for energy has been consistently increasing. The energy shortage and environmental pollution problems caused by the traditional energy development method which is based on fossil energy are becoming more and more prominent. The Energy Internet is a system of energy utilization with deep integration of energy and information technology, which can greatly improve the utilization of renewable energy and ensure more reliable, economical and convenient energy use [1-2].

The physical layer of the Energy Internet is based on the multi-energy cooperative energy network. By coordinating and optimizing the operation of multiple energy sources, the multi-energy collaborative energy network can improve the efficiency of each energy link and provide users with highly reliable, efficient, and clean energy supply [3]. As the most typical component of Energy Internet, the Energy Local Area Network (ELAN) is a key step in bringing the concept of energy interconnection from theory to practical engineering.

The planning for the multi-energy system should comprehensively consider the type of energy equipment selection, the number of configurations and the operation strategy, etc. [4-5]. Combining the energy, economic, environmental, load and policy factors of the region, the planning of park-type ELAN should reasonably determine the energy supply and demand structure of the park, as well as the positioning of the park. To take full advantages of the regional resources, the focus of the planning should be different for parks with different positioning. Meantime, the multi-energy cooperation optimization of the park-type ELAN should be also carried out in the planning process.
The main contributions of this paper are: according to the characteristics of the park industrial structure, the positioning of the park are analysed in and a physical planning architecture of the park-type ELAN is proposed; based on the proposed physical planning architecture, a planning method of the park-type ELAN is proposed, which can integrate the optimization problem of multi-energy cooperative scheduling into the planning model; an actual solid waste treatment park is taken as an example. The planning results show that the proposed planning method has significant improvements in energy, environment and economy.

2. Park-type ELAN planning structure

2.1. Park positioning

2.1.1. Classification of park. The parks can be divided into new parks and expansion parks according to their development status. New parks refer to parks that need to be planned from scratch, while expansion parks refer to parks that are upgraded from the existing ones. Among them, parks can also be subdivided into industrial parks, agricultural parks, business parks, tourism and cultural parks, and public service parks according to the characteristics of business activities.

The positioning of parks involves the determination of the park scale and load type. For new parks, energy, environment and policies constitute the resource elements of a park, and the park positioning need to be achieved on the premise of effective utilization. For the expansion park, it is necessary to conduct a study on the scale of park development and the layout of industrial structure. With the development of the park, the original facilities in the park are gradually unable to meet operation demands. The renovation and upgradation should be paid attention to in the planning and development of the park.

2.1.2. Analysis of the impact factors of the park.

(1) Energy factors

The clean energy availability determines whether it has enough potential to support the development and utilization of ELAN. Furthermore, it affects the choice of clean energy utilization methods and related equipment. Different types of clean energy have temporal and spatial differences, for example, wind energy has a dry wind period and solar energy has diurnal alternation. In addition, the reliability, environmental and economic benefits of different clean energy are different, which should complement each other as much as possible in the planning process. Clean energy usually has its special source, for example, agricultural parks have animal manure, and urban solid waste treatment parks have solid waste garbage that can be converted into biomass energy.

Table 1. Energy influence factors

| Type                     | Thermal storage                                      |
|--------------------------|------------------------------------------------------|
| Clean Energy Availability| Wind, Energy, Solar, Natural Gas                     |
| Clean Energy Complementarity| Space-time complementarity                          |
| Park Specificity         | Complementary reliability, environmental and economic benefits |
|                          | Conversion of biomass energy                         |

(2) Load factors

Table 2. Load characteristics of typical parks

| Type                  | Specific use         | Load characteristics                                                                 |
|-----------------------|----------------------|-------------------------------------------------------------------------------------|
| Industrial Park       | Chemical Park        | Higher demands for natural gas and heat; Self-contained heat source                  |
|                       | High-tech Park       | High power quality requirements; Smooth electrical loads                             |
| Agricultural Park     | Agri-farming Park    | The load is widely distributed and undemanding; Seasonal characteristics              |
| Business Park         | Malls                | High power consumption; Stable load during opening hours and no load off-work        |
| Residential Park      | Apartments           | The temporal characteristics are opposite to those of the business parks              |
| Culture Park          | Scenic Spot          | The load is closely related to the off-peak characteristics of visitors               |
| Public Service Park   | Treatment Park       | The electrical load can be negligible, the heat/cooling load shows seasonal characteristics, |
|                       | High School District | The electric heating and cooling loads have a clear temporal character                |
The parks present different industrial structures because of their different functional characteristics. Thus, their internal energy consumption characteristics will be different, specifically in terms of the variety, quantity, time and mode of energy demand.

(3) Environmental factors

The reduction of carbon and PM2.5 emissions in the park depends on the setting of the weights of environmental objectives, which are directly influenced by the capacity and operation of energy equipment such as natural gas and wind.

2.2. Physical planning structure

The physical planning structure of park-type ELAN can help determine the coupling mode and flow direction among various energy sources in the park and realize the multi-energy complementary cooperative optimization for the planning process.

The physical planning structure is divided into supply side, conversion side, transmission side, energy storage side, and load side. The impact factors are pinpointed to each part of the architecture based on the environmental, energy, and load factor analysis in the park positioning. The environmental factors are mainly related to the generation and conversion of energy, so they affect the supply side and conversion side components. The energy factor relates to the entire process of energy generation, conversion, transmission, and storage, so it affects all but the load side. The load factor is the last link in the whole architecture, and it can be traced back to every part of the architecture, so the load factor affects the whole physical planning architecture.

In addition, when building the physical planning structure, it is important to determine whether the park-level ELAN is new or expanded. The physical planning structure of a new park can be determined based on the positioning of the park, but an expanded park must consider its original physical structure. The construction process of the physical planning structure is in Figure 1.

![Figure 1. The process of the physical planning structure](image)

3. Planning model

In the planning model, the energy component parameters are the decision variables, and the objective is the annual cost of the park-type ELAN, which contains all the costs after the conversion of energy, economic and environmental aspects, as well as the operating costs. The operating costs are calculated from the collaborative scheduling optimization quantities of each energy element, which are limited by the parameters of the energy component. Thus, these two steps will be mutually constrained, and a realistic planning solution will be obtained after repeated iterations. This paper proposes a bi-level programming model for solving the problem. The total annual cost is the target of the upper layer model and the energy component parameter is the decision variable. The annual operating cost is the target of the lower layer model and the energy component scheduling quantity is the decision variable.

3.1. Upper layer model

3.1.1. Objective function. The objective of the upper layer model is the minimum annual cost $F_{up}$, which contains the investment cost of energy components $C_{inv}$, the operating cost $C_{ope}$, the clean energy subsidy
cost $C_{\text{allo}}$ and the environmental maintenance cost $C_{\text{ep}}$.

$$F_{\text{ep}} = C_{\text{m}} + C_{\text{ep}} + C_{\text{save}} - C_{\text{save}}$$  \hspace{1cm} (1)

$$C_{\text{m}} = \frac{r(1+r)t}{(1+r)^t-1} \left( \sum C_{i} V_{i} + \sum \min(L_{j,k}, t)(aC_{\text{L},i} + bC_{\text{L},i} + cC_{\text{L},i}) \right)$$  \hspace{1cm} (2)

Where $r$ is the annual discount rate, $L$ is the component life years. $C_{\text{L},i}$, $C_{\text{L},i}$, $C_{\text{L},i}$ are the unit capacity of component $i$ and the unit length investment cost of the electricity, gas, and heat network respectively. $a$, $b$, and $c$ are 0-1 state variables, 0 means no construction of the electricity, gas, and heat network. $V_i$ is the capacity of component $i$. $L_{j,k}$ is the path length between load $j$ and the $k$-th equipment side. $N$ is the number of components.

$$C_{\text{ep}} = \beta(1+\beta)^t \sum C_{i}^e V_{i}$$  \hspace{1cm} (3)

Where $\beta$ is the annual discount rate of environmental maintenance cost. $T_e$ is the environmental maintenance year. $C_{\text{ep},i}$ is the environmental maintenance cost per unit capacity (length) of element $i$, and $V_i$ is the capacity (length) of element $i$.

3.1.2. Constraint conditions. The constraints in the upper layer are divided into two main categories, one is the limit of the installable capacity of the energy components and the other is the mutual limit formed by the energy flow relationship within the park.

$$\begin{align*}
V_{\text{min}} & \leq V \leq V_{\text{max}} \\
G_i(V) & \leq 0
\end{align*}$$  \hspace{1cm} (4)

Where $V_{\text{min}}$, $V_{\text{max}}$ are the upper and lower limits of the installable capacity, and $G_i(V)$ is the constraint triggered by the energy flow relationship about the capacity. A solid waste treatment park is taken for case studies in this paper. The energy flow relationship within the solid waste treatment park can be expressed as follows.

$$\begin{align*}
\begin{cases}
0 \leq W_{\text{WL}} & \leq M_{\text{Waste}} , \quad 0 \leq W_{\text{WI}} & \leq M_{\text{Waste}} \\
M_{\text{Waste}} & \leq W_{\text{WL}} + W_{\text{WI}} , \quad W_{\text{O}_{\text{CH4}}} & \leq W_{\text{Waste}} + W_{\text{P2G}} \\
W_{\text{Waste}} - M_{\text{Waste}} & \leq W_{\text{WL}} + W_{\text{Waste}} , \quad W_{\text{P2G}} & \leq W_{\text{Waste}} + W_{\text{Waste}}
\end{cases}
\end{align*}$$  \hspace{1cm} (5)

Where $W_{\text{WL}}$ is the refuse landfill capacity. $W_{\text{WI}}$ is the capacity of waste incineration for power generation. $M_{\text{Waste}}$ is the daily amount of waste to in the park. $W_{\text{P2G}}$ is the amount of natural gas generated by P2G. $W_{\text{O}_{\text{CH4}}}$ is the amount of natural gas consumed by transport vehicles and ships in the park. $W_{\text{Waste}}$ is the amount of natural gas generated by the biogas compression and purification station. $M_{\text{Waste}}$, $M_{\text{Waste}}$ are the amount of leachate produced by landfill and waste incineration, respectively. $M_{\text{Waste}}$ is the treatment amount of leachate plant. $W_{\text{Waste}}$, $M_{\text{Waste}}$ are the amount of leachate produced by landfill and waste incineration, respectively.

3.2. Lower layer model

3.2.1. Objective function. The objective of the lower layer model is the minimum annual operating cost, including energy transaction fees $C_{\text{trade}}$, maintenance fees $C_{\text{man}}$, carbon emission cost $C_{\text{CO}_2}$ and cost saving cost $C_{\text{save}}$ due to increased utilization of renewable energy.

$$F_{\text{LOW}} = C_{\text{m}} + C_{\text{man}} + C_{\text{trade}} - C_{\text{save}}$$  \hspace{1cm} (6)

$$C_{\text{save}} = \sum (P_{\text{sell},t} \omega_{\text{sell},t} + V_{\text{sell},t} \omega_{\text{sell},t} - P_{\text{buy},t} \omega_{\text{buy},t} + V_{\text{buy},t} \omega_{\text{buy},t})$$  \hspace{1cm} (7)

Where $P_{\text{sell},t}$, $V_{\text{sell},t}$ are the amounts of electricity and gas sold at time $t$. $\omega_{\text{sell},t}$, $\omega_{\text{sell},t}$ are the selling prices of electricity and gas at time $t$. $P_{\text{buy},t}$, $V_{\text{buy},t}$ are the amounts of electricity and gas purchased at time $t$, and $\omega_{\text{buy},t}$, $\omega_{\text{buy},t}$ are the purchase prices of electricity and gas at time $t$.

$$C_{\text{m}} = \alpha_{\text{m}} \left( \sum_{t,i} \frac{\omega_{\text{sell},t}^2}{\eta_{\text{grid}}} D_{t,i} + \frac{\omega_{\text{sell},t}^2}{\eta_{\text{grid}}} \sum_{t,i} P_{\text{buy},t} + \frac{\omega_{\text{sell},t}^2}{\eta_{\text{grid}}} \sum_{t} V_{\text{buy},t} \right)$$  \hspace{1cm} (8)
Where $\omega_{tax}$ is the carbon tax, $x_{co2}^i$ is the amount of carbon dioxide emitted when the $i$-th component outputs a unit of energy, $x_{co2}^i_{grid}$, $x_{co2}^{egrid}$ are the amount of carbon dioxide emitted when conventional electricity and gas equipment outputs a unit of energy, and $\eta_{ggrid}$, $\eta_{egrid}$, are the energy transmission efficiency of the electricity and gas networks.

3.2.2. Constraint conditions. The lower-level constraints are divided into energy balance and component capacity limitation. The expression is as follows.

$$
\sum_j P_{load}^{out} + P_{net} + \sum_i P_{int}^i = P_{buy} + \sum_i P_{out}^i - P_{loss}^t,
$$

$$
\sum_j H_{load}^{out} + H_{net} = \sum_i H_{int}^i - H_{loss} + H_x,
$$

$$
\sum_j V_{load}^{out} + V_{net} = \sum_i V_{int}^i - V_{loss} - V_x,
$$

Where $P^{load}_{t,j}$, $H^{load}_{t,j}$, $V^{load}_{t,j}$ are the electrical, heat and gas loads. $P_{int}^i$, $H_{int}^i$, $V_{int}^i$ are the electrical, heat and gas quantities consumed by the components. $P_{out}^i$, $H_{out}^i$, $V_{out}^i$ are the electrical, heat and gas quantities produced by the components. $P_{loss}^t$, $H_{loss}^t$, $V_{loss}^t$ are the line electricity, heat, and gas losses. $H_x$ is the excess heat discharged. Component capacity limit means that the component cannot be dispatched beyond its capacity limit at time $t$. 

$$D_{min} \leq D_{t,i} \leq D_{max}
$$

4. Case study

A solid waste treatment park is used as an example for park-type ELAN planning. The original energy components of the park include a landfill, a waste incineration power plant, a leachate treatment plant, wind power and a biogas plant. In order to make full use of the various energy sources in the park, and reduce carbon emissions. This paper plans a biogas compression and purification station, P2G and energy storage equipment based on the original structure. Combining genetic algorithm and linear programming to solve the problem, the planning results are shown in Table.3.

| Type (original components) | Original capacity | New capacity |
|----------------------------|-------------------|-------------|
| Landfill                   | Nearly full       | 1270.81 t/d |
| Waste incineration power plant | 3000 t/d   | 5277.00 t/d |
| Leachate Treatment Plant  | 3200 m3/d        | 4102.54 m3/d|
| Biogas power plant        | 15MW             | 45kW        |

| Type (new planning)        | Original capacity | New capacity |
|----------------------------|-------------------|-------------|
| Biogas compression and purification station | / | 179211.38 m3/d |
| P2G                        | /                 | 654 kw      |
| Electricity Storage        | /                 | 470.67 kWh  |
| Thermal storage            | /                 | 91.2 kWh    |
| Gas Storage                | /                 | 255.31 m³   |

Table 4 is the environmental benefit comparison of the system, which shows that the environmental benefits of the multi-energy complementary system of the solid waste treatment park have been significantly improved. The CO2 emission reduction of the planned multi-energy complementary system is 2.61 times than the original system. In addition, the use of biogas as fuel for vehicles and ships can increase the CO2 emission reduction by 2776.4t/d compared to the use of gasoline.

Due to the single form of energy utilization, the efficiency of the original park is very low. As it can be seen in Table 5, the utilization form of biogas is richer, and the efficiency is greatly improved. The utilization rate of thermal energy in the original park is 0, while the utilization rate is 0.97 after planning. In addition, the biogas and natural gas achieve circulating in the system. Garbage and solid waste are transported to landfills and incineration power plants by vehicles and ships, where biogas and natural gas are generated after landfill and incineration. After the biogas is compressed and purified, it can be used as the fuels for vehicles and ships. The circulation of energy reduces the emissions and terminal treatment of biogas and reduces the environmental burden of economic growth.

Through multi-energy complementary planning, it can be seen form Table 6. that the external sales
of heat and gas have brought great economic benefits compared to the origin system which just have electricity sales revenues.

Table 4. Environmental benefit comparison of the system

| Type Application method | Original components | New Additional components |
|-------------------------|---------------------|--------------------------|
| Before planning         | Waste incineration power plant 1135.9 | Biogas power plant 88.9 |
| After planning          | 2968.6              | ~88.9                    |

Table 5. Energy benefit comparison of the system

| Type Application method | Biogas/natural gas | Thermal energy | Electric energy |
|-------------------------|--------------------|----------------|----------------|
| Before planning         | 0.467              | /              | /              |
| After planning          | 0                  | 0.16           | 0.95           |

Table 6. Economic benefit comparison of the system

| Type Application method | Economic/million |
|-------------------------|------------------|
| Before planning         | Investment 0.26  |
| After planning          | 1.63             |

5. Conclusion

This paper studies the planning method of park-type ELAN. Based on the characteristics of the industrial structure of the park, the method of physical planning structure of park-type ELAN with positioning analysis is proposed, which can facilitate the planning model to consider multi-energy coordination. The proposed planning method can simultaneously realize the planning and the optimized operation of multi-energy coordination within the park. The case study proves that the proposed planning method has significant energy, environment, and economic benefits.

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