Bi-level Planning Model for Integrated Energy Network in Solid Waste Treatment Park

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Abstract. In this paper, a bi-level planning model was proposed for the integrated energy network in solid waste treatment park to achieve optimal energy planning in the park. Firstly, the factors affecting planning were analyzed from the aspects of energy and environment. Then, the physical architecture of the integrated energy network planning of the solid waste treatment park was proposed, and the typical energy component models of the solid waste treatment park were proposed. This paper took the annual total cost as the first-level target and the annual operating cost as the second-level target, then proposed the bi-level planning model of the integrated energy network. Finally, the advantages of the model were verified by example. The example shows that under the action of the bi-level planning model, the energy, environment and economic benefits of the solid waste treatment park can be significantly improved.

1 Introduction

For the purpose of energy conservation and environmental protection, solid waste treatment plants such as landfills and waste incineration power plants have formed a solid waste treatment park with integrated energy sources based on the park [1].

When planning for the integrated energy network of the solid waste treatment park, the conventional site selection and capacity planning can achieve the energy, economic and environmental goals of the park-level energy LAN, but it has ignored the advantages of multi-energy coordination [2].

This paper proposed a bi-level planning model to plan the integrated energy network of the solid waste treatment park. The model considers energy, economic and environmental factors to effectively improve energy efficiency and maximize energy, economic and environmental benefits.

2 Influencing factors

From the perspective of energy and environment, this paper has analyzed the factors affecting the integrated energy network planning of the solid waste treatment park.

2.1 Energy factors

Unlike other industrial parks, solid waste treatment parks have a certain proportion of clean energy. Therefore, while considering the complementarity of its own clean energy, it is also necessary to consider whether other local clean energy sources are available, such as: wind energy, solar energy [3].

2.1.1 Assessment of wind energy and solar energy availability

For wind resources, it can generally be evaluated by parameters such as average wind speed, effective wind speed hours, and effective wind energy density. The average wind speed is the average of the wind speed over a certain period of time. The effective wind speed hour refers to the duration of the wind speed being the effective wind speed, and the average wind power density within the effective wind speed is the effective wind energy density.

For solar resources, it can be judged based on three parameters: annual radiation quantity, resource stability and direct ratio. The annual amount of radiation is the sum of the regional radiation during the year. The resource stability is expressed by the ratio of the maximum value and the minimum value of the number of days of sunshine per month greater than 6 hours. Direct ratio is the ratio of direct radiation to total radiation.

2.1.2 Multiple clean energy complementary

The reliability, environmental and economic benefits of different clean energy are different. They can make up for the defects as much as possible while complementing each other, so as to realize the complementarity of reliability, environment and economy in the integrated energy network of the solid waste treatment park [4]. Table 1 lists the reliability, environmental and economic
characteristics of existing and potentially available clean energy in solid waste treatment parks.

### Table 1. Comparison of clean energy characteristics in solid waste treatment parks

| Class            | Average Power Generation Cost (Yuan/kWh) | Carbon Emission (g/kWh) | Reliability |
|------------------|-----------------------------------------|-------------------------|-------------|
| Gas              | 0.25–0.45                               | 599                     | high        |
| Solar Energy     | 2.5–5                                   | 0                       | low         |
| Wind Energy      | 0.5–0.6                                 | 0                       | low         |
| Geothermal Energy| 0.45–0.9                                | 91                      | mid         |

#### 2.2 Environment factors

For solid waste treatment parks, it is often easy to overlook the environmental benefits of overall scheduling optimization [5]. In addition, for some parks, biogas treatment applications are still lacking, often directly burning emissions, resulting in increased carbon emissions costs. Therefore, appropriate environmental target weights should be set to reduce the impact of environmental factors on the final planning results.

### 3 Planning design

#### 3.1 Physical planning architecture

The physical planning structure of the integrated energy network of the solid waste treatment park shows the relationship of the energy coupling flow of the whole park [6,7], as shown in Figure 1.

![Solid Waste Network Integrated Energy Network Physical Planning Framework](image)

#### 3.2 Typical energy component model for solid waste treatment park

Typical energy components in solid waste treatment parks include waste incineration power plants, landfills, leachate treatment plants, biogas power plants, etc.

##### 3.2.1 Waste incineration power plant

Waste incineration power plants generate waste heat while burning waste to generate electricity. The expression is as follows.

$$E^W, Q^W$$ are the amount of power generation and residual heat, respectively. $$M_{W_{leach}}^W, M_{W_{obj}}^W$$ are the mount of leachate produced for burning waste. $$k_{W}^P$$ and $$k_{W}^H$$ are power generation efficiency and heat production efficiency. $$k_{W_{leach}}$$ is leach rate.

#### 3.2.2 Biogas power plant

$$E_{biog} = k_{biog} V_{biog}$$

$$E_{biog}$$ and $$V_{biog}$$ are the amount of electricity generated and the amount of biogas consumed. $$k_{biog}$$ is the power generation efficiency of biogas power plants.

#### 3.2.3 Landfill

Landfills are landfill sites that produce biogas and leachate after a period of reaction.

$$V_{W_{leach}}^W = \frac{2WY_{m}(1-\omega)(1-e^{-\gamma T})}{T}$$ \quad t < T

$$V_{W_{leach}}^W = \frac{2WY_{m}(1-\omega)(e^{\gamma T} - 1)e^{-\gamma t}}{T}$$ \quad t ≥ T

$$V_{W_{leach}}^W = k_{W_{leach}} M_{W_{leach}}$$

$$V_{W_{leach}}^W$$, $$m$$, $$k$$, $$t$$ and $$T$$ are biogas production, annual landfill volume, attenuation coefficient, year and landfill life. $$W$$ is wet garbage content. $$\omega$$ is the moisture content of wet garbage. $$V_{biog}$$ is the theoretical biogas production of unit dry garbage. $$k_{W_{leach}}$$ is the landfill rate of landfills. $$V_{W_{leach}}^W$$ and $$M_{W_{leach}}$$ are the leachate production and landfill volume.

#### 3.2.4 Leachate treatment plant

Biogas is produced during the treatment of leachate.

$$V_{biog} = \gamma_{biog} M_{W_{leach}}^{biog}$$

$$Q_{biog} = \gamma_{biog} M_{W_{leach}}^{biog}$$

$$M_{W_{leach}}^{biog}$$ is the amount of leachate treatment, $$V_{biog}^W$$ is biogas production, and $$Q_{biog}^W$$ is power production and heat consumption. $$\gamma_{biog}$$, $$\gamma_{biog}$$ and $$\gamma_{biog}$$ are gas production efficiency, power consumption efficiency and heat consumption efficiency.

### 4 Bi-level planning model

The upper model is targeted at the annual total cost, the energy component parameters are the decision-making amount, the lower model is the annual operating cost, and the energy component scheduling is the decision-making amount [8].

#### 4.1 Upper model

4.3.1 Upper objective function
The goal of the upper model is to minimize the annual fee \( F_{up} \), which includes investment costs for energy components \( C_{inv} \), operating expenses \( C_{ope} \), clean energy subsidy \( C_{allo} \) and environmental maintenance cost \( C_{epm} \).

\[
F_{up} = C_{inv} + C_{ope} + C_{allo} - C_{epm} \tag{6}
\]

### 4.3.2 Upper constraint

The upper layer constraints are mainly divided into two categories, one is the installable capacity limit of the energy component, and the other is the mutual restriction formed by the internal energy flow relationship of the park.

\[
V_{i,\text{min}} \leq V_i \leq V_{i,\text{max}} \tag{7}
\]

\( V_{i,\text{min}} \) and \( V_{i,\text{max}} \) are the upper and lower limits of the installable capacity. \( G_i(V_i) \) is a constraint on the energy flow relationship of the capacity.

### 4.2 Lower model

#### 4.2.1 Lower objective function

The target of the lower model is the minimum annual operating cost \( F_{low} \), which includes energy transaction fees \( C_{trade} \), maintenance fee \( C_{man} \), carbon cost \( C_{co2} \), Cost saving \( C_{save} \).

\[
F_{low} = C_{opm} + C_{man} + C_{trade} - C_{save} \tag{8}
\]

#### 4.2.2 Lower constraint

Lower layer constraints are divided into energy balance and capacity limits of components.

\[
\begin{align*}
\sum_{i} P_{in}^{t,i} + \sum_{j} P_{out}^{t,j} &= \sum_{i} P_{co2}^{t,i} - \sum_{i} P_{loss,t} \\
\sum_{i} H_{in,j} + \sum_{j} H_{out,j} &= \sum_{i} H_{co2}^{t,i} - H_{loss,t} \\
\sum_{i} V_{in,j} + \sum_{j} V_{out,j} &= \sum_{i} V_{co2}^{t,i} - V_{loss,t}
\end{align*}
\]

\( P_{in}^{t,i} \), \( H_{in,j} \), \( V_{in,j} \) are electric load, hot/cold load, gas load. \( P_{co2}^{t,i} \), \( H_{co2}^{t,i} \), \( V_{co2}^{t,i} \) are the electricity consumption, heat consumption, cold consumption, and gas consumption of component \( i \).

\( P_{loss,t} \), \( H_{loss,t} \), \( V_{loss,t} \) are line electricity, heat/cold, gas loss. \( H_e \) is the excess heat emitted, the value is a positive number.

| Table 2. Energy component parameters of the case park |
|------------------------------------------------------|
| **Element** | **Unit capacity equipment cost (Yuan)** | **Unit scheduling operation and maintenance cost (Yuan)** | **Effectiveness** |
| Landfill | 6.1429 | 0.84 | Gas production rate 3.418 m³/t |
| Waste incineration power plant | 3557.1 | 13.5 | Power generation rate 495.3 kWh/t |
| Leachate treatment plant | 18386 | 5.93 | Power consumption rate 32.7 kWh/m³ |
| Biogas power plant | 1700 | 0.0074 | Power generation rate 1.7 kWh/m³ |
| Wind power | / | / | / |
| Biogas compression purification station | 65 | 0.0525 | Gas production rate 50% |
| P2G | 800 | 0.042 | Conversion rate 0.45 m³/kWh |
| Storage | 142.86 | 0.00027 | Discharge 90% |
| Gas storage | 321.6 | 0.0315 | Inflatable 58.4% |
| Heat storage | 5 | 0.00024 | Deflation 75% |
| Photovoltaic | 8500 | 0.01 | Heating and heat release 90% |

| Table 3. Planned component capacity |
|-------------------------------------|
| **Component name** | **Capacity** |
| Landfill | 1064.52 t/d |
| Waste incineration power plant | 4896 t/d |
| Leachate treatment plant | 3628.71 m³/d |
| Biogas power plant | 4.16 kW |
| Biogas compression purification station | 146610.48 m³/d |
| P2G | 723 kW |
| Storage | 483.87 kWh |
| Heat storage | 87.10 kWh |
| Gas storage | 193.55 m³ |
5 Case analysis

This paper takes a solid waste treatment park as an example. The park is located on the seashore and has abundant wind energy resources. It is an energy self-sufficient park. However, there is a problem of direct combustion and emission of biogas, and the phenomenon of wind abandonment is serious. In order to improve energy efficiency, this paper plans biogas compression and purification station, P2G and energy storage equipment on the original basis. The physical planning framework is shown in Figure 2.

Because the solid waste treatment park belongs to the source park, there is basically no situation that the capacity of the park cannot meet the load of the park. Therefore, in the lower-level planning model, the optimal results are determined by fluctuations in the wind rate and energy price. This paper sets the park load to a fixed value. The energy parameters of the case park are shown in Table 2.

The planning results are shown in Table 3. Comparison of planning effects in energy, environment and economy, as shown in Table 4, Table 5 and Table 6.

It can be seen from Table 4 that the form of utilization and efficiency of thermal energy have been greatly improved. In addition, in the integrated energy network of the solid waste treatment park, biogas and natural gas have realized circulation in the system. In Table 5, the planned CO$_2$ emission reduction of the park is more than twice than the original. In addition, the use of biogas as fuel in vehicles and ships can reduce CO$_2$ emission by 2515.8t/d compared with conventional fuel. It can also be seen from Table 6 that the sale of electricity, heat and gas energy account for a large part of the economic benefits of park, and the economic benefits have been significantly improved.

### Table 4. Energy benefit comparison of the system

| Energy efficiency /% | Biogas/natural gas | Thermal energy | Electric energy |
|----------------------|--------------------|----------------|----------------|
| Application method   | Direct combustion  | Power generation | Car | For sale | Gas storage | Leachate treatment plant | Wind power |
| Before optimization planning | 0.467              | 0.533           | /   | /        | /           | 0               | 0.95       |
| After optimization planning | 0                  | 0.1             | 0.1 | ~0.8     | ~0          | 0.98            | 1          |

### Table 5. Environmental benefit comparison of the system

| Carbon emission reduction (t/day) | Waste incineration power plant | Biogas power plant | Car&Boat |
|----------------------------------|--------------------------------|--------------------|----------|
| Application method               | 1135.9                         | 88.9               | /        |
| Before optimization planning     | 2717.7                         | ~88.9              | 2515.8   |
| After optimization planning      |                                |                    |          |

### Table 6. Economic benefit comparison of the system

| Economic /million |
|------------------|----------------|
| Type             | Expenditure   |
| Application method | Investment | Operation and maintenance | Environmental maintenance | Carbon tax | Solid waste subsidy | External sales benefit |
| Before optimization planning | 0.26       | 0.64                      | 0.15                  | 69.2       | 0.548              | 0.6426                |
| After optimization planning    | 1.54       | 1.50                      | 0.20                  | 125.4      | 1.491              | 1.423                 |
5 Conclusion

This paper proposed the physical structure of the integrated energy network in the park. Combined with the unique energy components of the solid waste treatment park, an integrated energy bi-level planning model was proposed with the goal of minimum annual park fee. Combining genetic algorithm and linear programming to compare the effect of planning, it is concluded that the bi-level planning model proposed in this paper can effectively improve the energy efficiency, economic benefits and reduce carbon emission of solid waste treatment parks.

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