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A PLANNING METHOD FOR POWER SUPPLY SYSTEMS IN INDUSTRIAL PARKS CONSIDERING DEMAND RESPONSE

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ABSTRACT

Industrial parks have shown an important development trend of employing distributed generations instead of traditional centralized power supply. This paper studies the planning method of power supply systems in industrial parks, considering demand side response based on day-ahead real time pricing. An improved demand side response model is proposed to solve the imbalance of energy shifting and overwork of demand side response when price elasticity matrix is used. Furthermore, an optimal planning model is established, taking minimum total cost as the optimization objective, and solved by the GA-PS algorithm. Additionally, two indexes, the ratio of distributed generation deficiency energy and the ratio of distributed generation deficiency hours, are proposed to characterize the complementary of multi-energy. Finally, a case of a typical power supply system in an industrial park is given to validate the proposed method.

Keywords: multi-energy complementary, optimal planning method, power supply system in industrial parks, day-ahead real time pricing, demand side response

NONMENCLATURE

Abbreviations	
DG	distributed generations
RES	renewable energy sources
SSLC	source-storage-load coordination
RDGDE	the ratio of distributed generation deficiency energy
RDGDH	the ratio of distributed generation deficiency hours
EMS	management strategy
PEM	Price elasticity matrix
MDGDE	multi distributed generations deficiency energy
SDGDE	single distributed generation deficiency energy
MDGDH	multi distributed generations deficiency hours
SDGDH	single distributed generation deficiency hours
IIC	initial investment cost
RC	the replacement cost
OC	the operation cost
RER	renewable energy ratio in energy consumption
REDR	renewable energy dumping ratio
Symbols	
P_{WT}	the output power of WT
P_{PV}	the output power of PV
d	the output power of load
P_{BESS}	the output power of BESS
$P_{BESS\text{-}rate}$	the rated power of BESS
SOC_{min}	the minimum state of charge respectively
SOC_{max}	the maximum state of charge respectively
P_{grid}	the exchange power between the system and the power grid
W_{BESS}	the electricity shifted by BESS in a year
μ_0	the efficiency of the *BESS*.
s	an integer of 0 or 1*(*if $P_{WT\text{-}i}+P_{PV\text{-}i}-d_i$ >0, *s*=1*;* else *s*=0*)*
$P_{BESS\text{-}i}$	*t*he output power of *BESS* during period *i*
W_{grid}	the electricity shifted by BESS in a year
$P_{grid\text{-}i}$	the exchange power between the system and the power grid during period *i*

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Δd_i	the variations in the demand of consumers and the electrical price during period *i*
Δp_i	the variations in the demand of consumers and the electrical price during period d_i
E	price elasticity matrix
d_i	the base demand during period *i*
p_i	the base electrical price during period *i*
$\varepsilon_{i,j}$	the elasticity coefficient
β	the coeffcient of proportionality
$P_{\text{WT-}i}$	the output power of WT during period *i*
$P_{\text{PV-}i}$	the output power of PV during period *i*
$d_{\text{DR-}i}$	the consumer's demand
$\Delta d_{\text{shift-out}}$	the shift-out demand during hourly periods
$\Delta d_{\text{shift-in}}$	the shift-in demand during hourly periods
MDGDE	the gap between power energy produced by multi distributed generations and total customer's load
SDGDE	the gap between power energy produced by single distributed generation and total customer's load
K_{MDGDE}	the value of MDGDE
$K_{\text{SDGDE-}n}$	the value of SDGDE-*n*
R_{DGDE}	the rate of MDGDE and SDGDE
MDGDH	the gap between the hours supplied by multi distributed generations and the whole power supply hours
SDGDH	the gap between the hours supplied by single distributed generations and the whole power supply hours
K_{MDGDH}	the value of MDGDH
$K_{\text{SDGDH-}n}$	the value of SDGDH-*n*
R_{DGDE}	the rate of MDGDH and SDGDH
C_{total}	the minimization of the system total net present cost
m	the lifetime of the entire power supply system
r	the discount rate
C_{IIC}	the system IIC
C_{RC}	the RC every year
C_{OC}	the OC every year
C_{grid}	the cost for purchasing electricity from the power grid every year
C_{e}	the renewable electricity subsidy every year
C_{DARTP}	the cost of DARTP-DR implementation every year
V_{s}	the system residual value
C_{IIC}	the initial investment cost
$C_{\text{IIC-WT}}$	the system initial investment cost of WT system
$C_{\text{IIC-PV}}$	the system initial investment cost of PV system
$C_{\text{IIC-BESS}}$	the system initial investment cost of BESS
C_{RC}	the replacement cost
L_{BESS}	the service life of BESS
T_{BESS}	the replacement times of BESS
$C_{\text{RC-BESS}}$	the replacement cost of BESS
W_{BESS}	the electricity shifted by BESS
c_{BESS}	the batteries' cycle count
V_{BESS}	the volume of BESS
ρ_{DOD}	the depth of discharge
C_{OC}	the yearly operation cost
$C_{\text{OC-WT}}$	the yearly operation cost of WT
$C_{\text{OC-PV}}$	the yearly operation cost of PV
$C_{\text{OC-BESS}}$	the yearly operation cost of BESS
C_{grid}	the yearly cost for purchasing electricity from the power grid
p_0	the price for purchasing electricity from the power grid
C_{e}	the yearly renewable electricity subsidy
a_{WT}	the WT electricity subsidy
a_{PV}	PV's electricity subsidy
W_{WT}	the electricity supplied by WT system
W_{PV}	the electricity supplied by PV system
C_{DARTP}	the cost for DARTP-DR
k	the *k*th day in a year
p	the base price after DARTP-DR implementation during period *i* of the *k*th day in a year
$\Delta p_{k,i}$	the price change after DARTP-DR implementation during period *i* of the *k*th day in a year
$d_{k,i}$	the base demand after DARTP-DR implementation during period *i* of the *k*th day in a year
$d_{\text{DR-}k,i}$	the demand after DARTP-DR implementation during period *i* of the *k*th day in a year
X	the optimal variables
$P_{\text{WT-rate}}$	the rated output power of WT
$P_{\text{PV-rate}}$	the rated output power of PV
d_{DR}	the demand after DR implementation

1. INTRODUCTION

In recent years, China starts a new chapter in its electricity market reform, which aims to introduce market mechanisms to various areas in the power sector, including the electricity pricing mechanism and retail market. The reform also breaks up China's long-standing model that integrates transmission, distribution, and retail in a single entity, and distributed power supply becomes one of the important trends in the development of power supply systems. Because of the large power consumption, diversified forms of energies and relative independence of power supply systems, the industrial parks have become the most important pilot projects in this new round reform.

The traditional planning of power supply systems in industrial parks generally contains two aspects - load forecasting and network design. The emergence of distributed generations (DG) makes the optimal allocation of DGs become a key issue in the planning of a power supply system in an industrial park. With the deepening of reform in the distribution and retail side, the electricity pricing mechanism would be more flexible, and the time-space characteristics of customers' electricity behavior will be more deeply affected by the pricing mechanism.

Thus, further considering the demand side characteristic and DR has become an important issue in the current research on distribution network planning. Ould [1] studied the effect of the load profile variation on the optimal planning， which was carried out adopting three different load profiles having the same energy. Furthermore, the uncertainty of RES and demand was taken into calculation in order for all possibilities to be covered [2]. Guo [3] proposed a multi-objective stochastic optimal programming method and a stochastic chance-constrained programming model, including uncertainties of wind speed, clearness index and load demand. Baraffe [4] studied the long-term planning of the YLPIC distribution network by using the Smart Sizing tool, and presented some insights into the load and power generation flexibility in the network. A model was established in [5] to assess total supply capacity, taking into account daily load curves for different categories of customers such as residential, commercial and industrial. Ahmadian [6] proposed a methodology for optimal planning of stationary battery and dispatchable DG units considering the problems arising from the uncertainty of PEVs, which was represented by a fuzzy model. However, these research just focused on the characteristics of the supply side or demand side separately in optimal planning of distributed networks, while how to use SSLC to improve the power balance relationship in the distribution network still need further study.

The main target of this paper is to propose a planning method of power supply systems in industrial parks, based on an improved DARTP-DR model without imbalance of energy shifting and overwork of DARTP-DR. Additionally, in order to describe the complementary of multi-energy, RDGDE and RDGDH are proposed. Then, three methods are compared by simulation analysis, including the planning method without DR, the planning method with the traditional DARTP-DR and the planning method with the improved DARTP-DR, showing that the optimal planning with the improved DARTP-DR has a better effect on the reduction in the total cost of a power supply system in an industrial park.

2. OVERVIEW OF THE SYSTEM

A typical power supply system in industrial park is shown in Fig 1.

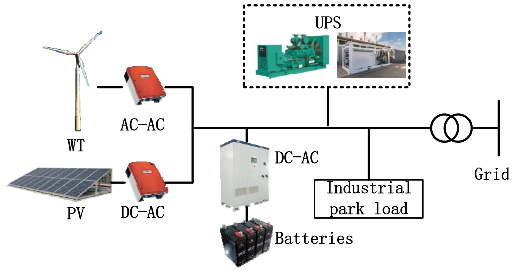


Fig 1 Configuration of the power supply system

The DGs/BESS planning in an industrial park is closely related to the EMS of the system, and the EMS used in this paper is shown in Fig 2.

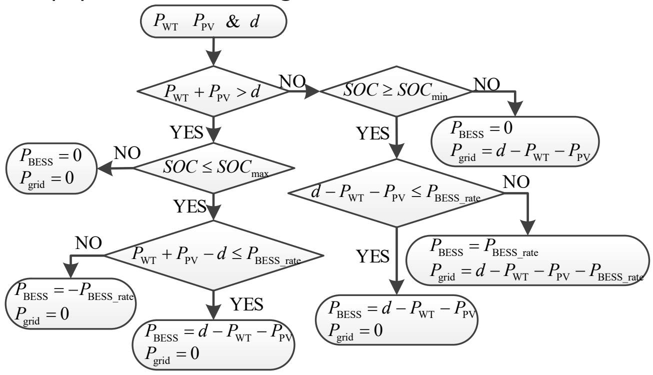


Fig 2 Flowchart of the EMS

According to the EMS described in Fig. 2, the electricity shifted by BESS in a year can be expressed as:

$$W_{\mathrm{BESS}}=\mu_0\sum_{i=1}^{8760} sP_{\mathrm{BESS}\text{-}i} \quad (1)$$

The electricity supplied by the power grid in a year can be expressed as:

$$W_{\mathrm{grid}}=\sum_{i=1}^{8760} P_{\mathrm{grid}\text{-}i} \quad (2)$$

3. DR MODELING

PEM is an important method for modeling DARTP-DR [7]. PEM is of the order 24×24 with hourly varying rates. The modeling of DARTP-DR can be described as:

$$\begin{bmatrix} \Delta d_1/d_1 \\ \Delta d_2/d_2 \\ \cdots \\ \Delta d_{24}/d_{24} \end{bmatrix} = \boldsymbol{E} \begin{bmatrix} \Delta p_1/p_1 \\ \Delta p_2/p_2 \\ \cdots \\ \Delta p_{24}/p_{24} \end{bmatrix} \quad (3)$$

And the demand variation in any time can be described as:

$$\Delta d_i = \sum_{j=1}^{24} \left(\varepsilon_{i,j} \times \left(\Delta p_j / p_j \right) \times d_i \right) \quad (4)$$

The variation of electrical price can be described as:

$$\Delta p_i = \beta (d_i - P_{\text{wt-}i} - P_{\text{pv-}i}) \quad (5)$$

Thus, with implementing DARTP-DR, the consumer's demand could be expressed as:

$$d_{\text{DR-}i} = d_i + \Delta d_i \quad (6)$$

Although the mathematical model of DARTP-DR has been established by using PEM, there are some problems existing in the process of solving DARTP-DR. First, equation (3)-(4) can't ensure there is no computation loss in demand after DARTP-DR. Second, the overwork of DARTP-DR causing unnecessary cost as shown in Fig 3 can't be avoid, which will decrease the economy of the planning scheme. For example, during the periods corresponding to area A, the demand is less than the RESs before DARTP-DR, and because of the overwork of DARTP-DR, the demand become larger than the RESs after DARTP-DR, which will lead to an extra use of BESS and no benefit for the cost reduction of electricity supply.

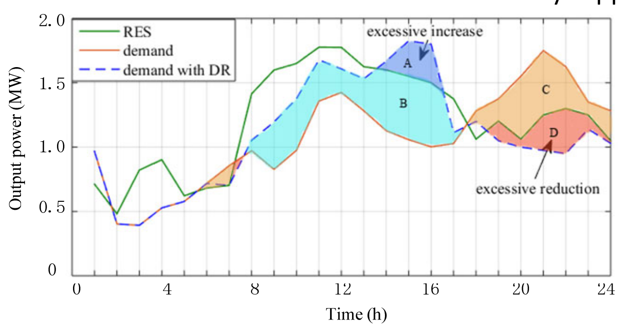


Fig 3 Overwork of DARTP-DR

Based on the aforementioned analyses, a correction is proposed for the model of DARTP-DR.

The change of demand during hourly periods calculated by (3)-(4) can be separated into the shift-out demand and the shift-in demand, described as:

$$\Delta d_{\text{shift-out}} = \sum_{i=1}^{24} m \Delta d_i \quad \text{if} \quad \Delta d_i < 0, \ m=1; \ \text{else} \ m=0 \quad (7)$$

$$\Delta d_{\text{shift-in}} = \sum_{i=1}^{24} n \Delta d_i \quad \text{if} \quad \Delta d_i > 0, \ n=1; \ \text{else} \ n=0 \quad (8)$$

If $\left|\Delta d_{\text{shift-out}}\right| \geq \left|\Delta d_{\text{shift-in}}\right|$, the change of demand can be corrected as:

$$\begin{cases} \Delta d_i^{'} = \Delta d_i & \Delta d_i > 0 \\ \Delta d_i^{'} = \Delta d_i \times \Delta d_{\text{shift-in}} / \Delta d_{\text{shift-out}} & \Delta d_i < 0 \end{cases} \quad (9)$$

If $\left|\Delta d_{\text{shift-out}}\right| < \left|\Delta d_{\text{shift-in}}\right|$, the change of demand can be corrected as:

$$\begin{cases} \Delta d_i^{'} = \Delta d_i & \Delta d_i < 0 \\ \Delta d_i^{'} = \Delta d_i \times \Delta d_{\text{shift-out}} / \Delta d_{\text{shift-in}} & \Delta d_i > 0 \end{cases} \quad (10)$$

4. INDEXES OF MULTI-ENERGY COMPLEMENTARITY

Two indexes, RDGDE and RDGDH, are proposed to describe the multi-energy complementarity in this paper.

RDGDE is the rate of MDGDE and SDGDE, and it can be calculated by

$$R_{\text{DGDE}} = \frac{2 \cdot K_{\text{MDGDE}}}{K_{\text{SDGDE-1}} + K_{\text{SDGDE-2}} + \cdots + K_{\text{SDGDE-}n}} \quad (11)$$

RDGDH is the rate of MDGDH and SDGDH, and it can be calculated by

$$R_{\text{DGDH}} = \frac{2 \cdot K_{\text{MDGDH}}}{K_{\text{SDGDH-1}} + K_{\text{SDGDH-2}} + \cdots + K_{\text{SDGDH-}n}} \quad (12)$$

5. OPTIMAL METHOD

5.1 Objective function

In this paper, the objective function is minimization of the system total net present cost which can be described as:

$$C_{\text{total}} = \frac{C_{\text{IIC}}}{1+r} + C_{\text{RC}} + \sum_{k=1}^{m} \frac{C_{\text{OC}} + C_{\text{grid}} - C_{\text{e}} + C_{\text{DARTP}}}{(1+r)^k} - V_{\text{s}} \quad (13)$$

The initial investment cost can be calculated as follows:

$$C_{\text{IIC}} = C_{\text{IIC-WT}} + C_{\text{IIC-PV}} + C_{\text{IIC-BESS}} \quad (14)$$

The replacement cost mainly caused by replacement of batteries in BESS, and it can be described as:

$$C_{\text{RC}} = C_{\text{RC-BESS}} \sum_{n=1}^{T_{\text{BESS}}} \frac{1}{(1+r)^{n \cdot L_{\text{BESS}}}} \quad (15)$$

The batteries' replacement times can be expressed as:

$$T_{\text{BESS}} = \text{round}\left(\frac{20 W_{\text{BESS}}}{\mu_0 c_{\text{BESS}} V_{\text{BESS}} \rho_{\text{DOD}}} \right) \quad (16)$$

The batteries' service life can be expressed as

$$L_{\text{BESS}} = \text{round}\left(20 / T_{\text{BESS}} \right) \quad (17)$$

The yearly operation cost can be expressed as:

$$C_{\text{OC}} = C_{\text{OC-WT}} + C_{\text{OC-PV}} + C_{\text{OC-BESS}} \quad (18)$$

The yearly cost for purchasing electricity from the power grid is:

$$C_{\text{grid}} = p_0 W_{\text{grid}} \quad (19)$$

The yearly renewable electricity subsidy is

$$C_{\mathrm{e}} = a_{\mathrm{WT}} \cdot W_{\mathrm{WT}} + a_{\mathrm{PV}} \cdot W_{\mathrm{PV}} \tag{20}$$

Essentially, DR adjusts the load curve by cutting down the customers' expenses, then reduces the cost of the power supply system, and achieves win-win results for customers and power companies finally. Thus, the cost for DARTP-DR can be expressed as:

$$C_{\mathrm{DARTP}} = \sum_{k=1}^{365} \left(\sum_{i=1}^{24} p \times d_{k,i} - \sum_{i=1}^{24} \left(\Delta p_{k,i} + p \right) \times d_{\mathrm{DR}\text{-}k,i} \right) \tag{21}$$

5.2 *Optimal variables*

Optimal variables are:

$$X = \left[P_{\mathrm{WT\text{-}rate}}, P_{\mathrm{PV\text{-}rate}}, V_{\mathrm{BESS}}, P_{\mathrm{BESS\text{-}rate}}, \beta \right] \tag{22}$$

5.3 *Constraints*

5.3.1 Power balance constraints

The power balance constraints are:

$$P_{\mathrm{PV}} + P_{\mathrm{WT}} + P_{\mathrm{BESS}} + P_{\mathrm{grid}} = d_{\mathrm{DR}} \tag{23}$$

$$0 \le P_{\mathrm{PV}} \le P_{\mathrm{PV\text{-}rate}} \tag{24}$$

$$0 \le P_{\mathrm{WT}} \le P_{\mathrm{WT\text{-}rate}} \tag{25}$$

$$0 \le d_{\mathrm{DR}} \tag{26}$$

$$\left| P_{\mathrm{BESS}} \right| \le P_{\mathrm{BESS\text{-}rate}} \tag{27}$$

$$P_{\mathrm{grid}} \ge 0 \tag{28}$$

5.3.2 *SOC constraint of BESS*

The SOC of BESS should satisfy:

$$SOC_{\min} \le SOC \le SOC_{\max} \tag{29}$$

5.4 *Solving procedures*

The detailed procedures are illustrated as follows:

Step 1: System initialization. This is the first step in reading system parameters, GA-PS [8], equipment, renewable resources, demand, PEM, and renewable power subsidies.

Step 2: Initialize random population.

Step 3: To every chromosome, calculate its power generation data of WT and PV; then, set day-ahead real time pricing according to the difference between power supply curve and load curve and use the DARTP-DR model to obtain the load curve after DARTP-DR; finally, calculate the operation data of BESS and power grid based on the EMS described in Fig. 2.

Step 4: Based on the results from step 3, use the objective function to calculate the fitness value.

Step 5: Check the solution is feasible or not. Stop the process if the best chromosome has been find; else, find the best chromosome now available and abandon the others.

Step 6: use pattern search to enhance elites and then make selection, crossover and mutation.

Step 7: Generate new population and repeat the process from step 3.

6. CASE STUDY

6.1 *Results*

TABLE 1 summarizes the results of three optimal planning methods. As can be seen, for the method with the improved DARTP-DR, the total cost is obtained \$3,981,511 which is lower than that of the method without DR (\$4,778,461) and the method with the traditional DARTP-DR (\$4,141,538).

In TABLE 2, it can be found that the indexes for the method with the improved DARTP-DR are the best, including energy directly supplied by RES, energy shifting by BESS, energy from power grid, RER and REDR.

Fig 4 shows the overwork of DR when using the traditional DR model, which will decrease the economy of the optimal planning scheme. During 10:00-16:00, the demand (the red line) is less than the RESs (the yellow line) before DR, and the demand with the traditional DR (the purple line) become larger than the RESs after implementing DR, which will lead to an extra use of BESS. Furthermore, the improved model of DR could eliminate this problem.

TABLE 1 The Results Optimal Planning

	without DARTP-DR	traditional DARTP-DR	improved DARTP-DR
$P_{\mathrm{wt\text{-}rate}}$	600kW	600kW	600kW
$P_{\mathrm{pv\_rate}}$	1,484kW	1,484kW	1,484kW
$P_{\mathrm{BESS\text{-}rate}}$	1,066kW	931kW	919kW
V_{BESS}	3,882kWh	3,623 kWh	3,589kWh
Replacement times of batteries	6	4	4
Price coefficient β	/	2.0977×10^{-4}	2.0931×10^{-4}
C_{total}	\$4,778,461	\$4,141,538	\$3,981,511

TABLE 2 Energy Utilization Indexes

	without DARTP-DR	traditional DARTP-DR	improved DARTP-DR
Energy directly supplied by RES	1,355,960 kWh/year	1,614,582 kWh/year	1,677,020 kWh/year
Energy shifting by BESS	509,000 kWh/year	342,113 kWh/year	320,674 kWh/year
Energy from power grid	2,,463,900 kWh/year	2,360,888 kWh/year	2,328,200 kWh/year
RER	42.13%	45.11%	45.87%
REDR	9.93%	7.51%	7.20%

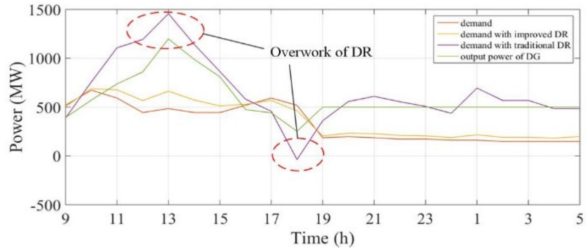
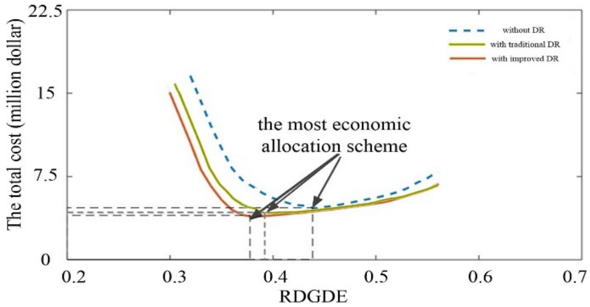
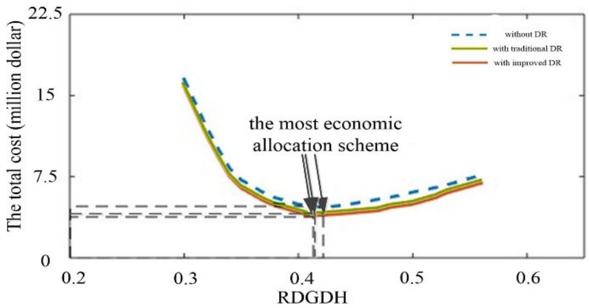


Fig 4 Overwork of DR

In order to further study the relationship between multi-energy complementary characteristics and optimal planning of power supply systems in industrial parks, an equality constraints of multi-energy complementary indexes are added in the model of optimal allocation. Fig 5 shows that R_{DGDE} and R_{DGDH} of the most economic optimal planning scheme are λ_o and ε_o, respectively. When the values of R_{DGDE} and R_{DGDH} are bigger than λ_o and ε_o, the total cost of the power supply system will decrease with the multi-energy complementary indexes increasing, mainly depending on the enhancement of multi-energy complementarity. When the values of R_{DGDE} and R_{DGDH} are smaller than λ_o and ε_o, the total cost of the power supply system will irrupt with the multi-energy complementary indexes increasing, mainly depending on increasing BESS to improve the multi-energy complementary characteristics. In addition, Fig 5 shows that DARTP-DR has a greater impact on RDGDE than on RDGDH.



(a) RDGDE



(b) RDGDH

Fig 5 Relationship between multi-energy complementarity and total cost of the power supply system

7. CONCLUSION

In order to solve the optimal allocation of DGs/BESS in industrial parks, this paper proposes a planning method considering a DARTP-DR, which helps to obtain a better economic planning scheme of DGs/BESS in industrial parks. However, for the price elasticity coefficients in the DARTP model are statistical data, and the customer number, the scale of electricity consumption is limited in an industrial park, there still is some deviation between the computation results and the actual situation. Thus, the mechanism of deviation and its impact on planning of power supply systems in industrial parks need to be further studied in the future.

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