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Optimal Retrofit and Evaluation Method of Integrated Community Energy System

Yan Cao[1*], Yan Qi[2], Congshan Wang[1], Qian Jiang[1], Qingzhu Zhang[1]

1 Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, China

2 Electric Power Research Institute, State Grid Tianjin Electric Power Company, Tianjin, China

ABSTRACT

With the promotion and application of multi-energy integration and distributed generation technologies, integrated community energy system (ICES) has developed rapidly. However, some ICESs have weak links such as poor economy, low energy efficiency, which restrict the effective operation of ICES. To solve this problem, an optimal retrofit method for ICES is proposed in this paper, which includes capacity expansion of the existing equipment and investment of new types of equipment. The proposed method takes the minimum total cost as the objective and sets equipment capacity and operation constraints during the process of retrofit. What's more, the economic index, primary energy efficiency and PV energy consumption rate are adopted to evaluate the effects of the retrofit. Finally, the effectiveness of this method is verified by the case study.

Keywords: integrated community energy system, retrofit, evaluation, planning

1. INTRODUCTION

Integrated community energy system (ICES) is a typical model of multi-energy complementation and joint supply on the user-side, which has been developed rapidly in recent years [1, 2]. ICES has effectively improved energy efficiency, the consumption of renewable energy, the reliability of energy supply [3].

Nevertheless, in some existing ICESs, there are some weak links such as the mismatch between the equipment capacity and the load demand, low photovoltaic consumption capacity, and so on [4]. Most of these problems result from the inaccurate preliminary planning scheme, change in energy prices, and other aspects.

Some studies have been done to solve the above problems. A multi-stage planning method for ICES considering the construction sequence is proposed in [5], this method divides the planning period into several stages, which can improve the energy supply economy and promote photovoltaic consumption. And an operation optimization method for ICES that considers part-load performances of devices is proposed in [6], which can save the actual operating cost of ICES.

This paper proposes an optimal retrofit method of ICES to reduce the bad effects of weak links and improve the operation efficiency of ICES. And the effects of the proposed retrofit method of ICES are verified by the case study.

2. MODEL OF INTEGRATED COMMUNITY ENERGY SYSTEM

A typical ICES is shown in Fig 1, which is composed of energy production, conversion, and storage equipment.

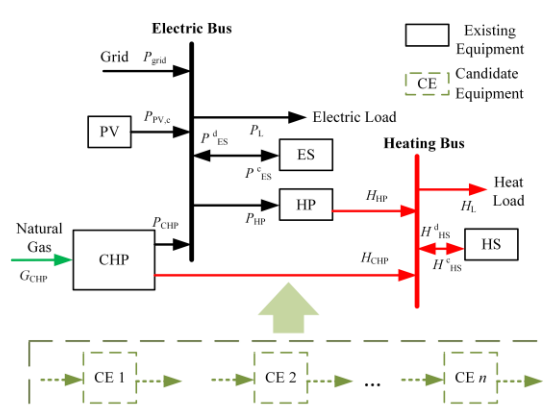

Fig 1 Model of ICES

Existing equipment includes photovoltaic (PV), electricity storage (ES), heat storage (HS), combined heat and power system (CHP), and ground source heat pump (HP). ICES is connected with the external grid and can exchange power with it.

As for the retrofit of ICES, the first way is to expand the capacity of existing equipment, the second way is to add new types of candidate equipment into the ICES. As shown in Fig 1, during the process of retrofit, various types of new candidate equipment will be connected into the ICES to form new energy conversion relationships.

3. OPTIMAL RETROFIT AND EVALUATION METHOD OF ICES

3.1 Optimal retrofit model of ICES

3.1.1 Objective function

The retrofit of ICES takes the minimum total cost C as the objective function, which includes the annual value of equipment investment cost and annual operation and maintenance cost. The expression of C is stated as:

$$C=C_{\mathrm{I}}+C_{\mathrm{O}}+C_{\mathrm{M}} \tag{1}$$

where C_{I} is the annual value of equipment investment cost; C_{O} is the annual operation cost; C_{M} is the annual maintenance cost.

The investment cost C_{I} includes the investment cost for expansion of ICES's existing equipment and the investment cost for newly added types of equipment. Assuming that there are k types of existing equipment in ICES and m newly added types of equipment, the expression of C_{I} is stated as follows:

$$C_{\mathrm{I}}=\sum_{i=1}^{k} R_i c_{i,\mathrm{I},old} P_{i,\mathrm{I},old}+\sum_{j=1}^{m} R_j c_{j,\mathrm{I},new} P_{j,\mathrm{I},new} \tag{2}$$

$$R_i=\frac{r(1+r)^{n_i}}{(1+r)^{n_i}-1} \qquad R_j=\frac{r(1+r)^{n_j}}{(1+r)^{n_j}-1} \tag{3}$$

where R_i and R_j are the annual value coefficients of the existing i-th type or newly added j-th type of equipment, r is the discount rate, which is 3% in this paper; n_i and n_j are the lifetime of the existing i-th type or newly added j-th type of equipment; $c_{i,\mathrm{I},old}$ is the investment cost per unit capacity of the existing i-th type of equipment, and $P_{i,\mathrm{I},old}$ is the expansion capacity of the existing i-th type of equipment, i = 1, 2, ⋯, k; $c_{j,\mathrm{I},new}$ is the investment cost per unit capacity of the newly added j-th type of equipment, and $P_{j,\mathrm{I},new}$ is the allocation capacity of the newly added j-th type of equipment, j = 1, 2, ⋯, m.

The annual operation cost C_{O} includes electricity purchase cost and gas purchase cost, as below：

$$C_{\mathrm{O}}=\sum_{t=1}^{8760}\left(c_{\mathrm{grid}}(t) P_{\mathrm{grid}}(t) \Delta t+c_{\mathrm{gas}} G_{\mathrm{Gas}}(t) \Delta t\right) \tag{4}$$

where $c_{\mathrm{grid}}(t)$ is the electricity price at time t; c_{gas} is the price of natural gas; $P_{\mathrm{grid}}(t)$ and $G_{\mathrm{Gas}}(t)$ are the electric power purchased from the external grid and the consumption power of natural gas at time t; Δt is the dispatch period, which is 1 hour in this paper.

The annual maintenance cost C_{M} consists the maintenance cost of the existing equipment and the maintenance cost of the newly added equipment; the expression of C_{M} is stated as:

$$C_{\mathrm{M}}=\sum_{t=1}^{8760} \sum_{i=1}^{k} c_{i,\mathrm{M},old} P^i(t) \Delta t+\sum_{t=1}^{8760} \sum_{j=1}^{m} c_{j,\mathrm{M},new} P^j(t) \Delta t \tag{5}$$

where $c_{i,\mathrm{M},old}$ is the maintenance cost per unit power of the existing i-th type of equipment; $P^i(t)$ is the output power of the existing i-th type of equipment at time t. $c_{j,\mathrm{M},new}$ is the maintenance cost per unit power of the newly added j-th type of equipment, $P^j(t)$ is the output power of the newly added j-th type of equipment at time t.

3.1.2 Constraints

1) Constrains for equipment capacity and operation

During the process of ICES's retrofit, for the existing energy storage equipment, its capacity S_{ESS} should be increased after capacity expansion.

And for the existing energy production and conversion equipment, its operation margin becomes larger after capacity expansion. Taking the existing i-th type of equipment as an example, its operation constraint after retrofit is as follows:

$$\begin{cases} P_{\mathrm{out}}^i(t)=P_{\mathrm{in}}^i(t) \eta_i \\ 0 \leq P_{\mathrm{out}}^i(t) \leq \bar{P}_{\mathrm{U}}^i \\ \bar{P}_{\mathrm{U}}^i=\bar{P}_{\mathrm{O}}^i+P_{i,\mathrm{I},old} \end{cases} \tag{6}$$

where $P_{\mathrm{out}}^i(t)$, $P_{\mathrm{in}}^i(t)$ and η_i are respectively the output energy power, input energy power, energy conversion efficiency of the existing i-th type of equipment; $\bar{P}_{\mathrm{O}}^i$ and $\bar{P}_{\mathrm{U}}^i$ are the upper limits of the output power of the existing i-th type of equipment before and after retrofit respectively.

For newly added energy production and conversion equipment, it needs to meet the energy conversion relationship and the limits of output. Taking the newly added *j*-th type of equipment as an example, its model is stated as:

$$\begin{cases} P_{\text{out}}^{j}(t) = P_{\text{in}}^{j}(t)\eta_j \\ 0 \le P_{\text{out}}^{j}(t) \le P_{j,\text{l},new} \end{cases} \tag{7}$$

where $P_{\text{out}}^{j}(t)$, $P_{\text{in}}^{j}(t)$ and η_j are respectively the output energy power, input energy power, energy conversion efficiency of the newly added *j*-th type of equipment.

2) Constrains for power balance

The electricity power balance constraint is described as:

$$\sum_{i=1}^{k} P_i^{\text{gen}} + \sum_{j=1}^{m} P_j^{\text{gen}} = P_{\text{L}} + \sum_{i=1}^{k} P_i^{\text{con}} + \sum_{j=1}^{m} P_j^{\text{con}} \tag{8}$$

where P_{L} denotes the power of electrical load; P_i^{gen} and P_i^{con} represents the generation power and consumption power of the existing *i*-th type of equipment respectively; P_j^{gen} and P_j^{con} represents the generation power and consumption power of the newly added *j*-th type of equipment.

And the heat power balance constraint is described as:

$$\sum_{i=1}^{k} H_i^{\text{gen}} + \sum_{j=1}^{m} H_j^{\text{gen}} = H_{\text{L}} + \sum_{i=1}^{k} H_i^{\text{con}} + \sum_{j=1}^{m} H_j^{\text{con}} \tag{9}$$

where H_{L} denotes the power of heat load; H_i^{gen} and H_i^{con} represent the heat generation and heat consumption power of the existing *i*-th type of equipment respectively; H_j^{gen} and H_j^{con} represent the heat generation and heat consumption power of the newly added *j*-th type of equipment respectively.

3.2 Evaluation indexes

The total cost, primary energy utilization efficiency, and PV energy consumption rate are utilized to evaluate the effects of the retrofit of ICES.

1) Total cost

The total cost *C* is used to quantify the economics of ICES. For ICES before retrofit, *C* includes the annual operation costs and annual maintenance costs incurred by ICES. For ICES after retrofit, *C* is calculated by (1).

2) Primary energy utilization efficiency

The primary energy utilization efficiency of ICES is defined to reflect the improvement of energy efficiency of the ICES after retrofit, which is as follow:

$$F = \frac{\sum_{t=1}^{T} P_{\text{L}}(t) + H_{\text{L}}(t)}{\sum_{t=1}^{T} \frac{P_{\text{grid}}(t)}{\eta_{\text{e}}\eta_{\text{grid}}} + P_{\text{pv}}(t) + G_{\text{gas}}(t)} \tag{10}$$

where *F* is the primary energy utilization efficiency; $P_{\text{L}}(t)$ and $H_{\text{L}}(t)$ are the electric and heat load power at time *t*; $P_{\text{pv}}(t)$ is the maximum output power of PV at time *t*; η_{e} and η_{grid} are average generation efficiency and transmission efficiency, which are 0.5 and 0.8 respectively.

3) PV energy consumption rate

To evaluate the efficiency of PV, the PV energy consumption rate is defined as:

$$\lambda_{\text{PV,c}} = \frac{\sum_{t=1}^{n} P_{\text{PV}}(t)\Delta t}{\sum_{t=1}^{n} P_{\text{PV,c}}(t)\Delta t} \times 100\% \tag{11}$$

where $\lambda_{\text{PV,c}}$ is the PV energy consumption rate; $P_{\text{PV,c}}(t)$ is the actual consumption power of PV; *n* is the number of periods included in the measurement interval.

4. CASE STUDY

A typical existing ICES is adopted in the case study, whose model is shown in Fig 1. The initial capacity and parameters of the existing equipment are shown in Table I. The maximum output curve of PV and the electric and heat load curves are shown in Fig 2, the data is composed of three typical daily data of each month. The ICES adopts the time-of-use electricity price, which is 1.35 yuan/kWh, 0.9 yuan/kWh and 0.47 yuan/kWh for peak, average, and valley periods respectively. The price of natural gas is 0.24 yuan/kWh.

Table I. Equipment's initial capacity and parameters

Type of equipment	Initial capacity	Investment cost per unit capacity (yuan)	Maintenance cost per unit power (yuan)
PV	1000kW	10000	0.039
CHP	120kW	7000	0.05
HP	135kW	3000	0.05
ES	450kWh	780	0.026
HS	875kWh	35	0.013
GB	0	700	0.03
EB	0	1000	0.04

Through the investigation and analysis of the operation status of the existing ICES in the early stage, it is found that there are some weak links in the coupling

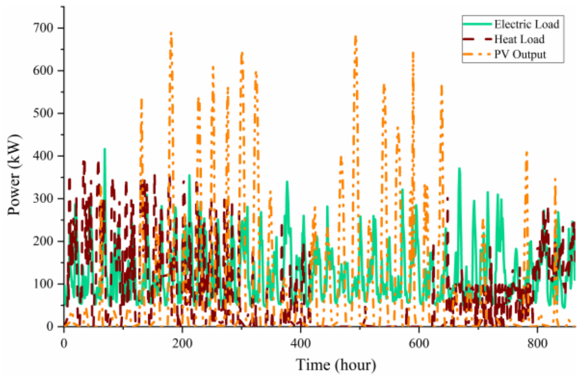

Fig 2 Load curves and PV output curve

link of PV and ES as well as the heat link. First, the overall PV energy consumption rate is low because of the large initial PV allocation capacity and the relatively small ES capacity. Second, with the increase of load in the park, the gap between supply and demand of heat energy increases, but the capacity of HP is too small. These weak links have restricted the normal operation of ICES and leaded to the increase of operation cost.

Therefore, it is necessary to retrofit the ICES to improve the operation status. Besides the capacity expansion of the existing equipment, gas boiler (GB) and electric boiler (EB) are selected as the newly added candidate equipment to strengthen the heat link, whose parameters are shown in table I.

4.1 Retrofit results

The expansion capacity of existing equipment and allocation capacity of GB and EB are shown in Table II. After retrofit, 19kW GB and EB are added to the ICES, and the capacity of HP is also expanded slightly, which improves the heat link. The capacity of ES is increased largely, which is beneficial to the consumption of PV. The capacity of CHP and HS is not expanded.

Table II. Retrofit results of each equipment

Equipment type	CHP	HP	ES	HS	GB	EB
Capacity allocation	0kW	5kW	1087kWh	0kWh	19kW	19kW

4.2 Evaluation of the effects of retrofit

The various indexes in Section 3.2 of ICES before and after retrofit are calculated, as shown in Table III. Through the retrofit, the economics of the ICES is improved, the total cost is saved by 0.107 million yuan per year. And the primary energy utilization efficiency is increased to 71.40%, indicating that the retrofit improves the energy efficiency. At the same time, the PV energy consumption rate increases to 74.66%, an increase of 20.56% compared to the ICES before retrofit because of the capacity expansion of ES. As a result, the output fluctuation of PV can be greatly suppressed by ES.

Table III. Indexes before and after retrofit

Index	Total cost(million yuan)	Primary energy utilization efficiency	PV energy consumption rate
Before retrofit	0.687	68.37%	56.10%
After retrofit	0.580	71.40%	74.66%
Improvement	15.60%	3.03%	20.56%

5. CONCLUSIONS

An optimal retrofit method of ICES is proposed in this paper. Expanding the capacity of existing equipment and adding new equipment are carried out in this method. And the effects of retrofit are evaluated through the quantification of various indexes. The results of the case study show that the proposed retrofit method can improve economics, PV energy consumption capacity, and primary energy utilization efficiency.

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