Energy Proceedings
Vol 36, 2023
ISSN 2004-2965

Collaborative Optimization of Regional Distributed Energy Systems Considering Load Timing Characteristics

Tingting Xu[1], Yingjun Ruan[1*], Fanyue Qian[1], Hua Meng[1], Guangyue Chen[1]

1 College of Mechanical and Energy Engineering, Tongji University, Shanghai 201804, China

* Corresponding author. E-mail address: ruanyj@tongji.edu.cn

ABSTRACT

Due to their environmentally friendly and energy-saving characteristics, regional distributed energy systems (RDES) have become one of the important ways to enhance renewable energy consumption and promote low-carbon society in recent years. The bottleneck of using peak load of user nodes in the division of energy supply scope at energy stations without full considering the load timing characteristics is addressed in this paper. Furthermore, this paper proposes a collaborative optimization method that considers load timing characteristics. Firstly. the coupling characteristics between energy stations and pipeline network are analyzed. Then a collaborative optimization design model for energy stations and pipeline networks is constructed based on K-means and graph theory algorithms. Subsequently, considering the load timing characteristics to analyze their impact on REDS. The research results indicate that considering the load timing of user nodes can reduce the cooling load demand of energy stations by 19.05% and the total pipeline cost by 8% compared to using peak loads. This paper provides theoretical and technical guidance significance for decision-makers of regional distributed energy systems.

Keywords: regional distributed energy system; energy station; pipeline network; load timing characteristics

NONMENCLATURE

Abbreviations	
RDES	Regional Distributed Energy System
TAC	Total Annual Cost
O&M	Operation and Maintenance
DA	Dijkstra Algorithm
GA	Genetic Algorithm
Symbols	
n	Year
C_{pl}	yuan
C_{es}	yuan
C_{pl}^{inv}	yuan
A_{pl}	/
C_{pl}^{p}	yuan
$C_{pl}^{\Delta Q}$	yuan
C_{pl}^{α}	yuan
M	/
m	/
ΔQ	W
$C_{es,m}^{e}$	yuan
$C_{es,m}^{c}$	yuan
$C_{es,m}^{h}$	yuan

1. INTRODUCTION

Facing with the global energy crisis and climate change, renewable energy is regarded as an important solution to alleviate environmental problems due to its inexhaustible nature [1]. However, with the large-scale integration of renewable energy, the power system will exhibit significant "dual randomness" and "triple double" characteristics of "double peaks and double heights", leading to the problem of renewable energy consumption becoming one of the bottlenecks.

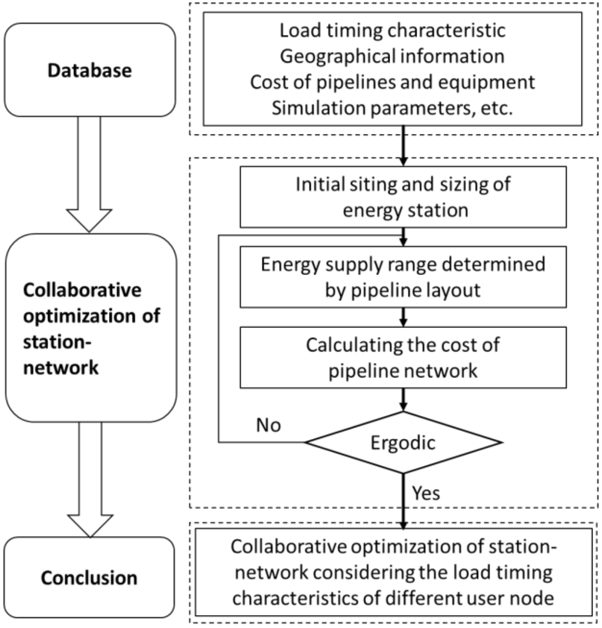

Fig.1 Research content

This is a paper for the 9th Applied Energy Symposium: Low Carbon Cities and Urban Energy Systems (CUE2023), Sep. 2-7, 2023, Matsue & Tokyo, Japan.

The construction of a regional distributed energy system (RDES) has great significance for promoting the transformation of energy structure, achieving high energy efficiency, and promoting the consumption of renewable energy [2]. RDES can be divided into three levels based on its scale: cross regional level, regional level, and user level. The research on RDES is the foundation of comprehensive analysis of wide area energy. RDES consists of energy stations, energy supply pipelines, and load centers. The planning of energy stations and supply pipelines needs to be coordinated with urban planning. Its rationality not only affects the smooth implementation of comprehensive energy projects, but affects the reliability and economy of the construction and operation of RDES on the later stage [3,4]. Research has shown that in regional cooling systems, the cost of pipeline networks often accounts for 30-40% of the total project investment. Therefore, studying scientific and reasonable layout planning methods for energy stations and supply pipelines have great significance for the development of RDES. RDES planning and design include three aspects: energy station configuration, facility location and network topology layout, and pipe diameter optimization. Existing research are lacking of integrity and systematicity [5-7].

In the process of optimizing the regional comprehensive energy system, the load demand calculation for a certain pipeline is calculated by adding the peak load for the user node. However, due to the different types of buildings have different load characteristics, the time points at which the peak load occurs are therefore different. Thus, directly calculating the peak load causes a larger calculation result. Considering the timing characteristics nature of load for different user node can help reduce the annual cost of the entire pipeline system and make the design more reasonable.

In summary, although current research at home and abroad has achieved certain results in addressing the issues of siting and sizing of energy station and pipeline network. Facing the expanding scale of energy systems and increasingly complex energy supply networks, due to the lack of systematic station-network optimization design methods, the phenomenon of relying on empirical conventions in the initial planning and design of energy utilization from the large power grid to the user end is caused. Therefore, this paper conducts research on RDES station-network collaborative optimization planning based on the consideration of load timing characteristics. The research content is shown as Fig.1. The introduction and relevant research for RDES are summarized in Chapter 1. Chapter 2 proposes the methodology used in this paper. Chapter 3 discussed the results. And the conclusion is drawn in Chapter 4.

2. METHODOLOGY

2.1 Paper structure

For the designing and planning of RDES, it consists of three aspects including of siting and sizing of energy stations, optimizing of pipeline networks, and configurating the installation of energy station capacity. We firstly determine the initial siting of energy station based on K-means cluster and energy distance method. Then calculate the corresponding cost of pipeline networks. Through continuously iterating the location of energy stations and pipeline network layout, the information of the station network is ultimately determined. For the optimization process, the load timing characteristic of different user node are fully considered.

2.2 Economic model of RDES

The economics of RDES are closely related to the number of energy stations, site selection, and network layout. In this study, the total annual cost (TAC) of RDES includes the total cost of pipeline networks and energy stations, mainly related to the energy loss of the pipe network, pipe diameter, flow rate, capacity of energy stations, and the location and layout of the station network. The TAC can be estimated to:

$$\mathrm{TAC} = C_{pl} + C_{es} \tag{1}$$

where C_{pl} is the total annual cost of pipeline networks, yuan; C_{es} is the total annual cost of energy stations, yuan.

The total annual cost of pipeline networks includes the construction investment cost, operation and maintenance (O&M) cost, energy loss cost, and pump cost, it can be calculated as:

$$C_{pl} = C_{pl}^{inv} A_{pl} + C_{pl}^{p} + C_{pl}^{\Delta Q} + C_{pl}^{\alpha} \tag{2}$$

where C_{pl} is the total annual cost of the pipe networks, yuan; A_{pl} is the cost annualization factor of pipeline; C_{pl}^{inv} is the initial construction cost of the pipeline networks, yuan; C_{pl}^{p} is the annual operation cost of the circulating water pump, yuan; $C_{pl}^{\Delta Q}$ is the annual depreciation cost of energy loss of the pipeline networks, yuan; and C_{pl}^{α} is the annual depreciation and maintenance cost of the pipe networks, yuan. ΔQ is to the amount of cold loss of the pipe network system, W. The total annual cost of energy stations is calculated:

$$C_{es} = \sum_{m \in M} C_{es,m} = \sum_{m \in M} (C_{es,m}^{e} + C_{es,m}^{c} + C_{es,m}^{h}) \tag{3}$$

where, M is the set of energy stations; m is energy station m. where $C^{e}_{es,m}$ is the annual cost for electricity supply of energy station m, yuan; $C^{c}_{es,m}$ is the annual cost for cooling supply of energy station m, yuan; $C^{h}_{es,m}$ is the annual cost for heating supply of energy station m, yuan.

2.3 Collaborative optimization of energy station and pipeline network

As the number of energy stations is a discrete variable and countable, the optimal number of energy stations can be determined through a large cycle. In this paper, the number of energy stations is calculated from 1 to 16, and the optimal results are ultimately retained.

The determination of the initial site of energy station is given using K-means clustering. The cluster center obtained is used to the initial site of the energy station. Then, K-means clustering is combined with energy distance to iteratively obtain better energy station location. The energy distance is the product of user node and its actual distance from energy station, reflecting the impact of the user node load distribution.

Due to the fact that the optimization of pipeline network layout can be clearly expressed using graph theory, it is often applied in the study of pipeline network layout in RDES. Dijkstra Algorithm (DA) is one type of the graph theory, it reflects the minimum distance of two different nodes. In the research of pipeline network optimization, the minimum distance of user node and energy station are obtained by DA. Genetic Algorithm are used to definite the calculation order of different user node in the research area.

The research logic of this paper is elaborate in Fig.2. We firstly determine the initial results of siting and sizing energy stations. The optimal pipeline network is then obtained according to the method of GA and DA. On the basis of economic model of RDES, which is expressed in section 2, the annualized of pipeline network are therefore calculated and compared. Until the number of energy station reached the upper limit, the optimal siting and sizing of energy stations, optimal pipeline network, dimeter of pipeline sections are outputted.

3. RESULT AND DISCUSSION

Scenario 1 is aimed at using a series method rather than collaborative optimization method in station-network optimization. In scenario 2, when considering the timing nature of user node loads, peak load addition is directly used. While the update of the cost weight adjacency matrix in Scenario 3 is based on the actual maximum load value of each pipeline segment. Fig. 3 shows a comparison of planning results without considering load timing (a) and considering load timing (b). Table 1 shows the cost comparison of the pipeline

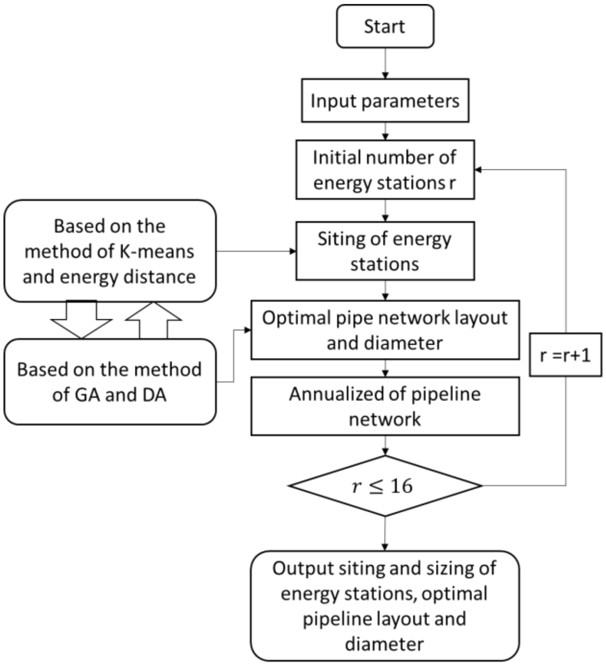

Fig. 2 Research flow

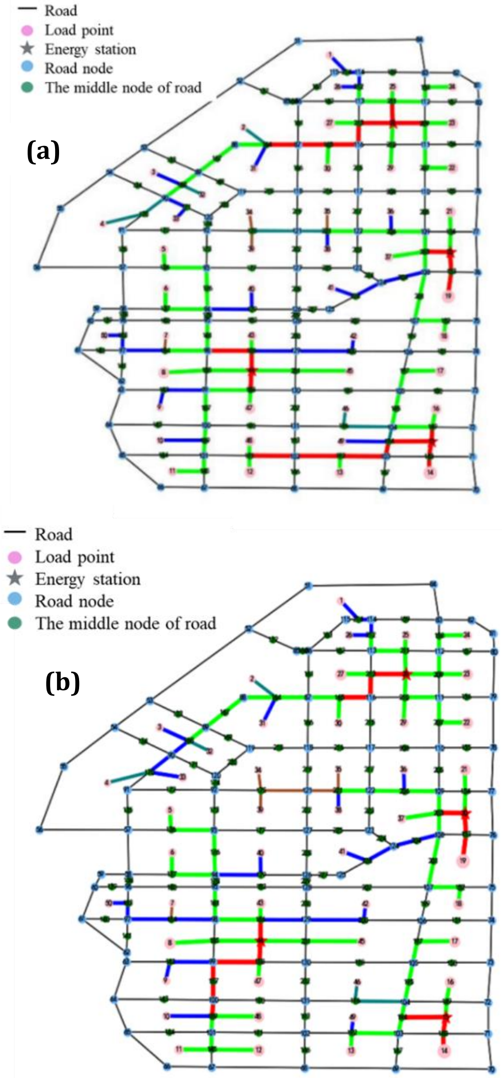

Fig.3 The comparison of pipeline network layout with considering timing nature of user node and not

network system. Compared to Scenario 1 and Scenario 2, Scenario 2 using the collaborative optimization algorithm reduces the pipeline network cost by 17% compared to Scenario 1 using the cascade algorithm. The main reason is that the location of energy stations in the series algorithm did not consider the impact of pipeline layout, resulting in the energy station not being located at the load center, thereby increasing the total cost of the pipeline network. Comparing Scenario 2 and Scenario 3, as the planning algorithm process in the two schemes is consistent, the difference lies in the different methods for determining the load. Due to the consideration of the load timing of user node, the load demand of different pipe sections has actually decreased (as shown in Fig. 3). Compared with Fig. (a) and Fig.3 (b), more red pipes were used, that is, more pipes with larger diameters were used for without considering the load timing. Due to the decrease in load demand is directly reflected in the pipeline network cost, the cost of pipeline network in scenario 3 has decreased by 8% compared to scenario 2 (as shown in Table 1). Since the consistent algorithm process, the cost reduction of each part of the pipeline system is also basically the same. From the results, considering the load timing of user nodes in the entire research area is more reasonable to plan the energy system.

Table 1 Comparison of pipeline costs under different scenario

Scenario	Construction cost, (*10^6Yuan)	O&M cost, (*10^6Yuan)	Energy loss, (*10^6Yuan)	Pump cost, (*10^6Yuan)
Scenario 1	12.7	3.6	0.9	6.6
Scenario 2	11.5	3.3	0.9	4.1
Scenario 3	10.6	3.0	0.9	3.8

4. CONCLUSION AND DISCUSSION

This paper constructs a collaborative optimization model for RDES that considers the temporal characteristics of user node loads. Through case studies, it can be concluded that this method simultaneously achieves unified planning of the number of energy stations, location of energy stations, pipeline network layout, and pipe diameter selection while considering the timing characteristics of different user node.

1) Compared with traditional serial planning processes, adopting collaborative optimization methods can effectively reduce the investment cost of pipeline systems, resulting in a 17% reduction in pipeline costs. At the same time, this method can make the load distribution within the energy supply area more reasonable, and also reduce the various costs of the pipeline system, which is conducive to the economic planning of the entire energy system and improves the efficiency of energy utilization.

2) By considering the temporal nature of user node load, the cooling load of energy stations has been reduced, resulting in an 8% reduction in pipeline network costs. Considering the load timing of energy consuming buildings in the entire load area can increase the rationality of RDES.

The current collaborative optimization algorithm still has many shortcomings. On the one hand, the user node data used in this study is simulated data obtained by EnergyPlus, which is not from the measured-value. On the other hand, the user load used in this paper is fixed, it is appropriate to consider the uncertainty of the load for the future research.

ACKNOWLEDGEMENT

This research has been supported by China's National Natural Science Foundation (No.51978482).

REFERENCE

[1] Xu, T., Gao, W., Qian, F., Li, Y. The implementation limitation of variable renewable energies and its impacts on the public power grid. Energy, 2022(293): 121922. (Reference to a journal publication)

[2] Wang YL, Wang JY, Gao MC, et al. Cost-based siting and sizing of energy stations and pipeline networks in integrated energy system[J]. Energy Conversion and Management,235,2021,113985. (Reference to a book)

[3] Di W, Li ZJ, Ha ZH, Ma FF, et al. Developing an equipotential line method for the optimal design of an energy station location in a district heating system. Energy Conversion and Management,210,2020,112708. (Reference to a book)

[4] Yan RJ, Wang JJ, Zhu ST, et al. Novel planning methodology for energy stations and networks in regional integrated energy systems[J], Energy Conversion and Management, 2020,205,112441. (Reference to a book)

[5] Liu H, Xiang C, Ge S, et al. Synergy planning for integrated energy stations and pipe networks based on station network interactions. International Journal of Electrical Power and Energy Systems, 2021(125): 106523. (Reference to a journal publication)

[6] Zhou Y, Ma Y, Wang J, et al. Collaborative planning of spatial layouts of distributed energy stations and networks: A case study[J]. Energy, 2021(234): 121205. (Reference to a journal publication)

[7] Yu Z, Li H, Yuan T, et al. Site Selection and Pipe Network Optimization Method of Regional Energy Station Based on Cluster Analysis and Minimum Spanning Tree[J]. HVAC, 2018, 48(9): 99-104. (Reference to a journal publication)