Energy Proceedings
Vol 43, 2024
ISSN 2004-2965

Dynamic Optimization of Energy Station Layout in District Energy Systems Considering Temporal Load Characteristic

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ABSTRACT

In the design of district energy systems, the optimization of energy station layout plays a pivotal role in catering to decentralized load demands and cost reduction. This research accounts for distinct temporal load distribution characteristics and streamlines the complex spatiotemporal distribution issue of large-scale load systems through scenario partitioning and optimization decomposition. The utilization of DBSCAN clustering method is employed to ascertain the configuration of energy stations and load assignments within each scenario. The overarching objective is to minimize the annual equivalent cost of the system, integrating the shortest path algorithm to refine energy station placements and pipeline layouts. Practical engineering cases validate the effectiveness of this approach. The study amalgamates temporal analysis to dynamically optimize energy station quantity, locations, and pipeline layouts, culminating in heightened economic viability and adaptability in the planning process, ultimately resulting in a comprehensive quantitative analysis of energy station design.

Keywords: District Energy, Dynamic Design, DBSCAN Clustering, Shortest Path

1. INTRODUCTION

In the wake of ongoing societal progress and the swift pace of urbanization, urban planning and development have encountered formidable challenges in the domains of energy supply and distribution. In response, district energy systems have emerged as a prominent and extensively researched field, aiming to amalgamate and expand the utilization of renewable energy resources. The objective is to fulfill the energy demands of clustered buildings while concurrently diminishing energy consumption, all in pursuit of sustainable urban development[1].Despite the theoretical potential of district energy systems, their practical applications have not yielded satisfactory results [2]. The advantages of applying renewable energy in district energy systems cannot offset the disadvantages of high investment and energy consumption. To address this issue, numerous scholars worldwide have conducted research: Georgilakis et al. [3]argue that the key to ensuring economic feasibility lies in the number of energy stations, their locations, and network layouts.Marguant et al. [4] broke down the complex problem of large-scale regional energy supply into manageable optimization sub-problems, contributing to the optimization of urban-scale energy systems. Wang Zhonghua et al. [5] introduced a novel optimization algorithm for pipeline network layouts that effectively combined genetic algorithms with local search methods. Hailkarainen et al. [6] took a comprehensive approach by considering alternative energy supply centers, pipeline topology, thermal energy storage, and variable consumer demands, optimizing both network layout and system operation.Jing et al. [7] proposed a hierarchical approach that decomposed problems into smaller sub-problems, addressing uncertainties in demand through stochastic programming and optimizing the number of energy stations.Xu Chengsi et al. [8] developed a topological description model for regional integrated energy systems, aiming to minimize initial investment and operational costs through layout planning.Wang Zhaoqiang et al. [9] optimized the number, locations, capacities, and network paths of energy stations using the minimum spanning tree concept and exhaustive search. Yi Wenfei et al. [10] established an optimization model for energy station site selection and pipeline layout, applying an enumeration method to solve the proposed models. Yu Zhen et al. [11] utilized K-means

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

clustering and minimum spanning tree algorithms for optimizing cooling and heating supply scopes and pipeline routes in a quantitative assessment and design optimization process. Wu et al. [12] developed a cost-oriented theoretical model for centralized heating systems, creating cost contour maps to aid in determining optimal energy station locations.

In summary, existing methods for energy station site selection and layout planning often rely on static planning approaches that primarily consider the spatial distribution of regional loads. However, due to the characteristics of district energy systems, such as large coverage areas, long construction periods, complex user conditions, and uncertain resource conditions, more dynamic and flexible planning methods are needed. This paper presents an optimization method for dynamic energy station site layout considering load construction phases. Since the model takes into account the temporal and spatial distribution characteristics of loads, its complexity increases rapidly. Therefore, this study proposes a hierarchical approach. Firstly, it divides the loads in the region into different construction scenarios based on the similarity of construction times. Each scenario is analyzed separately. Secondly, it divides the entire optimization design into two stages: the first stage determines the allocation of loads and the form of energy stations, while the second stage determines the locations of energy stations and network layouts. The proposed method comprehensively considers the optimization of energy station quantity, site selection, and network layout, providing decision support for the full quantitative analysis of energy station planning in a dynamic context.The specific research route is shown in Figure 1.

2. .METHODOLOGY FOR ENERGY STATION TYPOLOGY DETERMINATION AND LOAD ALLOCATION PLANNING BASED ON DBSCAN ALGORITHM

2.1 Methodology

This study introduces a novel methodology for determining energy station types and optimizing load allocation using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm. During the project planning phase, comprehensive data, including coordinates, load capacities, and construction schedules for various load points, are gathered. To account for the temporal aspects of load distribution, load points are categorized into distinct scenarios based on their construction timelines. Within each scenario, the construction formats of energy stations and load assignments are meticulously outlined. Special attention is given to scenarios where it is advantageous to construct energy stations separately for load points that are geographically distant and exhibit substantial load demands. The study employs a density-based DBSCAN clustering algorithm to group load points within the region. Notably, load values are integrated as influencing factors for algorithmic weighting. Figure 1 depicts the flowchart illustrating the clustering analysis method employed for energy station site selection. In this figure, "eps" denotes the neighborhood distance parameter in the DBSCAN algorithm, while "MinPts" signifies the minimum number of samples required in the neighborhood for a point to be considered a core point.

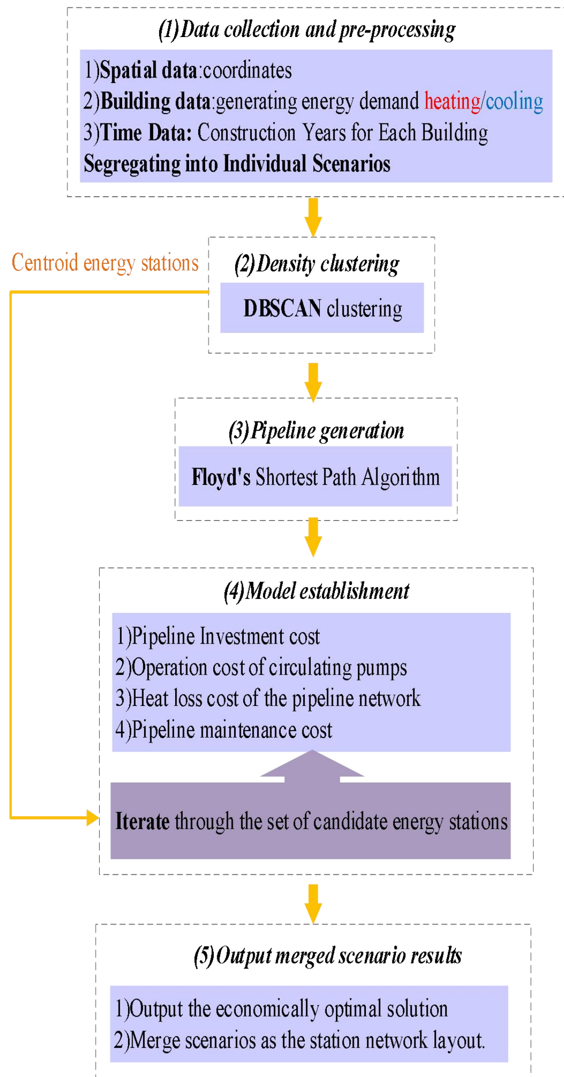

Figure 1: Outline of the technical roadmap

2.2 Introduction of Load Clustering Results in Different Scenarios

Taking a specific project as a background, which consists of 17 parcels, each with location information and load value magnitudes as shown in Figure 2, the parcels are now being segmented into different scenarios for the analysis of energy station construction forms.

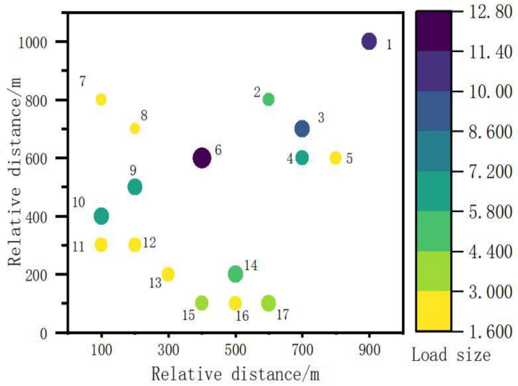

Figure 2: Load Information and Spatial Distribution Map

2.2.1 Static Case

Static methods exclusively account for the spatial distribution of individual plots while overlooking their temporal distribution. Consequently, static analysis is confined to the present scenario, yielding load allocation and energy station construction modalities. In this particular instance, three energy stations are established, and their corresponding coordinates and installed capacities, determined via clustering centroids, are elucidated in Table 1.Substation Centralized

Table 1: Energy Station Construction Information under Static Methods

Construction Status		Type	Coordinates	Load(MW)
Phase 1	S1	S	(820, 1020)	10.12
	S2	C	(700, 675)	22.72
	S3	C	(290, 438)	54.54

2.2.2 Dynamic Analysis Case 1:

In the context of large-scale regional energy systems, the subdivision into multiple stages serves the purpose of mitigating initial investment expenses and securing construction viability. In this specific scenario, the project is bifurcated into two distinct construction phases: Phase 1 encompasses parcels #1-6, while Phase 2 encompasses parcels #7-17. Consequently, it is partitioned into two distinct scenarios contingent upon construction batches, and the outcomes derived from clustering are graphically represented in Figure 3.

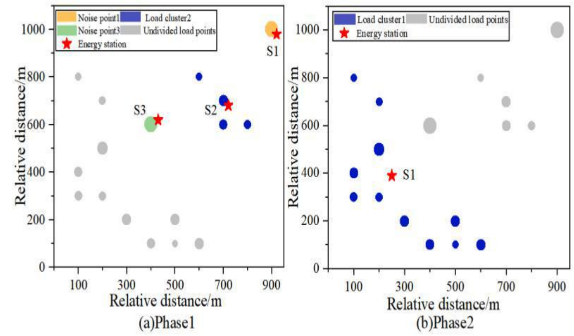

Figure 3 Clustering Results in Dynamic Case 1

From the clustering results, it can be observed that the allocation of loads and the construction forms of energy stations in this case are as follows: In Phase 1 of the project, three energy stations are constructed, including two energy substations and one centralized energy station. In Phase 2, one centralized energy station is constructed, resulting in a total of four energy stations. The specific information for the energy station construction in each phase is provided in Table 2.

Table 2 Energy Station Construction Information for Dynamic Case 1

Construction Status		Type	Coordinates	Load(MW)
Phase 1	S1	S	(820, 1020)	10.12
	S2	C	(700, 675)	22.72
	S3	S	(290, 438)	12.8
Phase 2	S1	C	(165, 395)	41.74

2.2.3 Dynamic Case Study 2

In Case 2, the project undergoes subdivision into four distinct construction phases. Phase 1 encompasses land parcels #1-5, Phase 2 pertains to land parcel #6, Phase 3 incorporates land parcels #7-12, and Phase 4 encompasses land parcels #13-17. This division leads to the creation of four discrete scenarios, with clustering outcomes visualized in Figure 4.

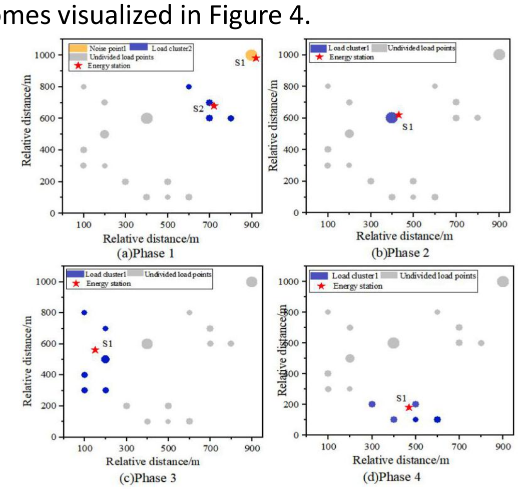

Figure 4: Clustering Results in Dynamic Case Study 2

Based on the clustering results, it is evident that the load allocation and energy station construction forms for this case study are as follows: in Phase 1, two energy stations will be constructed; in Phase 2, one substation will be built; and in Phases 3 and 4, one centralized energy station will be constructed for each phase. Consequently, a total of five energy stations will be constructed for this project. Detailed information regarding the energy station construction for each phase is presented in Table 3.

Table 3: Energy Station Construction Information for Dynamic Case Study 2

Construction		Type	Coordinates	Load(MW)
Phase 1	S1	S	(820, 1020)	10.12
	S2	C	(700, 675)	22.72
Phase 2	S1	S	(290, 438)	12.8
Phase 3	S1	C	(178, 577)	21.02
Phase 4	S1	C	(482,185)	20.72

2.3 Comparative Analysis of Cases

The clustering results for different scenarios in various cases were consolidated into a single chart, as depicted in Figure 5. hods exhibited variations among different scenarios.

From this comparative analysis, it becomes evident that static design methodologies, primarily reliant on geographic parcel information to ascertain the quantity and configuration of energy stations, frequently entail the simultaneous construction of the entire energy station and network to cater to both present and future demands. Such an approach results in substantial upfront investments and relatively heightened risks. Conversely, for expansive regional settings, a more rational strategy involves the phased, dynamic construction rooted in specialized regional energy plans. This approach permits enhanced adaptability to evolving factors within the region, thereby mitigating uncertainties. It serves to curtail initial investment risk, with its inherent flexibility and adaptability contributing to the enhancement of regional energy system sustainability and efficiency. This, in turn, enables better accommodation of shifting demands and resource condition.

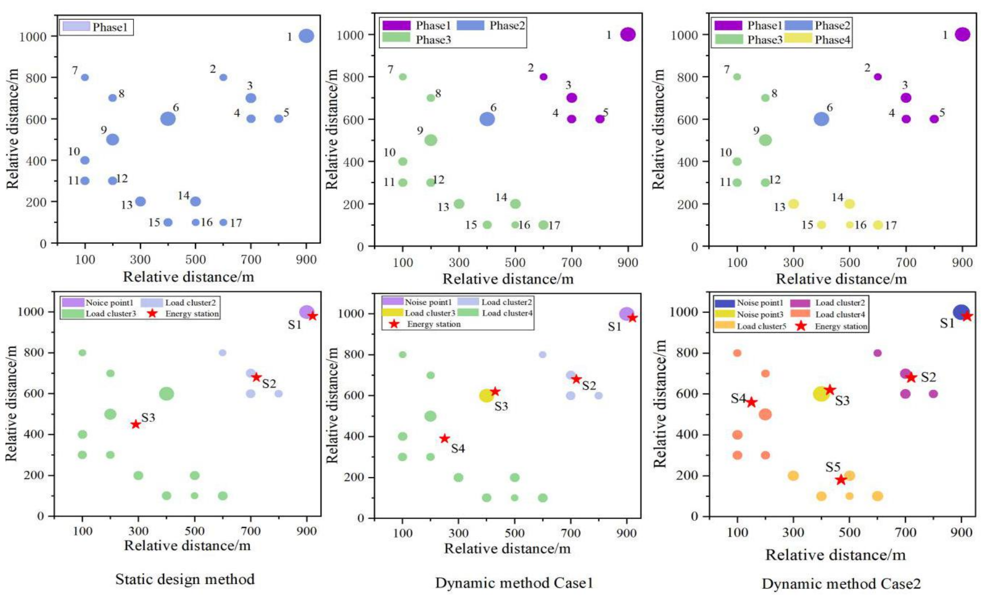

Figure 5: Comparative Clustering Results for Dynamic and Static Scenario Division

3. ENERGY STATION AND INTERCONNECTION PIPELINE LAYOUT PLANNING METHOD COMBINING THE FLOYD SHORTEST PATH ALGORITHM

3.1 Floyd's Shortest Path Algorithm

Upon determining the construction configuration of energy stations and load allocations, it becomes imperative to optimize both the site selection for energy stations and the pipeline network layout. Site selection is influenced by a confluence of factors including natural attributes, national policies, and urban planning guidelines, while the pipeline design must adhere to the urban planning road layout, with a primary aim of minimizing the aggregate pipeline length. This section proposes an energy station and network site selection method that combines graph theory and the Floyd shortest path algorithm.

3.2 . Model establishment

As load attribution has been determined in the previous section, this section solely describes the mathematical modeling of the pipeline network Eq. (1) illustrates the initial investment cost model for the pipeline network.Where C_0^{PL} represents the initial investment in pipelines, $d_i l_i$ represents the diameter and the length of segment i of the pipeline N is the number of pipeline segments; $C(d_i)$ represents the unit cost of segment i of the pipeline in yuan per meter.

$$C_0^{PL} = \sum_{i=1}^{N} C(d_i) l_i \quad (1)$$

Eq. (2) presents the operating cost of circulating pumps, where C_f^{PL} represents the annual operating cost of the circulating water pump, F_p represents the design flow rate of the circulating water pump in m3/s; P_p represents the operating pressure of the circulating water pump in Pa; C_e represents the electricity price in yuan/kW•h; η_p represents the electromechanical efficiency of the water pump; T_p represents the maximum annual operating time of the circulating water pump in hours.

$$C_f^{PL} = \frac{P_p \times F_p}{\eta_p} T_p C_e \times 10^{-7} \quad (2)$$

Eq. (3) presents the thermal loss cost of the pipeline network, where t_p represents the average water temperature in the pipeline network per year; t_o represents the average temperature of the surrounding medium of the pipeline network; $k$represents the average heat transfer coefficient of the pipeline network, typically ranging from 1.1 to 1.5 W/m2℃; r represents the unit price of thermal energy in yuan/kWh; τ represents the number of hours the pipeline network operates in a year.

$$C_L^{PL} = \sum_{i=1}^{N} 10^{-8} k\pi (t_p - t_o) 1.2 r\tau d_i l_i \quad (3)$$

Eq. (4) presents the maintenance cost of the pipeline : where: C_m^{PL} represents the annual depreciation and maintenance cost of the pipeline in yuan; μ_1^{PL} represents the depreciation rate; μ_2^{PL} represents the maintenance cost coefficient.

$$C_m^{PL} = (\mu_1^{PL} + \mu_2^{PL}) C_0^{PL} \quad (4)$$

the objective aims to minimize the total cost including the system design and operation cost, which is formulated by Eq. (5)

$$\mathrm{Obj} = \min\left(\frac{1}{T} C_0^{PL} + C_f^{PL} + C_L^{PL} + C_m^{PL}\right) \quad (5)$$

Traversing the set of alternative energy station locations and solving the objective function.This method can traverse the solution space to obtain all feasible solutions and ensures that the obtained solution is the optimal one, avoiding the possibility of obtaining suboptimal solutions as in the case of genetic algorithms.

3.3 CASE STUDY

In this section, we utilize the load allocation information determined in the previous scenario, as shown in Figure 6. There are a total of 17 demand points in this region, numbered from 1 to 17. Following the principles of energy station site selection and considering the resource conditions within the project planning area, this study identifies the locations of 7 pre-selected energy stations (numbered 18 to 24) in areas near extraction points and demand points but away from the bustling city center. There are 167 road nodes (numbered 24 to 190). To minimize pipeline length, the demand points are connected to the roads in a perpendicular manner.

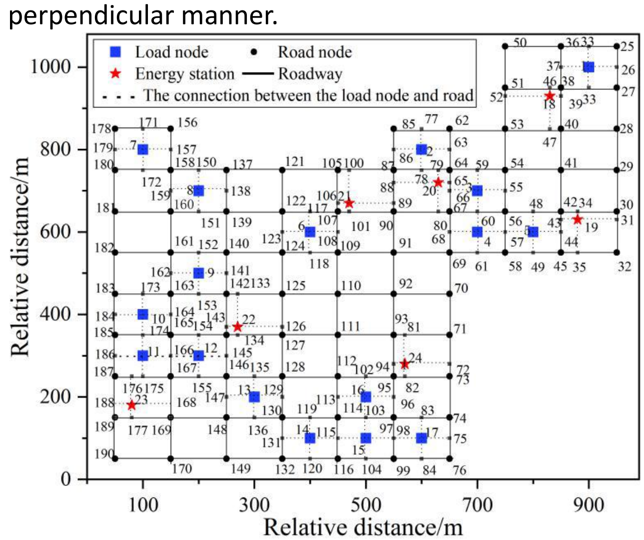

Figure 6: Regional Road Node Map

By implementing the energy station layout and site selection methodology expounded in the paper, we have ascertained the most favorable network configuration for energy stations. This encompasses the shortest routes connecting energy stations to demand nodes, along with particulars concerning the energy station capacities. These insights are meticulously outlined in Table 4.

Table 4. Shortest Path and load Information

Construction information			Shortest Path	Load (MW)
P1	18	1	1、33、46、18	10.12
	20	2	2、78、79、20	22.72
		3	3、60、67、65、20	
		4	4、60、67、65、20	
		5	5、48、67、65、20	
	21	6	6、108、106、21	12.8
P2	23	7	7、157、168、23	41.74
		8	8、159、168、23	
		9	9、162、168、23	
		10	10、164、168、23	
		11	11、166、168、23	
		12	12、166、168、23	
		13	13、136、169、168、23	
		14	14、116、169、168、23	
		15	15、103、169、168、23	
		16	16、103、169、168、23	
		17	17、83、169、168、23	

The optimization outcomes for the energy station and network layout in Case 2 are depicted in Figure 7. In this figure, the star-shaped points connected by pipelines denote the positions of energy stations determined using both the shortest path and economic optimization criteria. Additionally, the algorithm furnishes the optimal network layout.

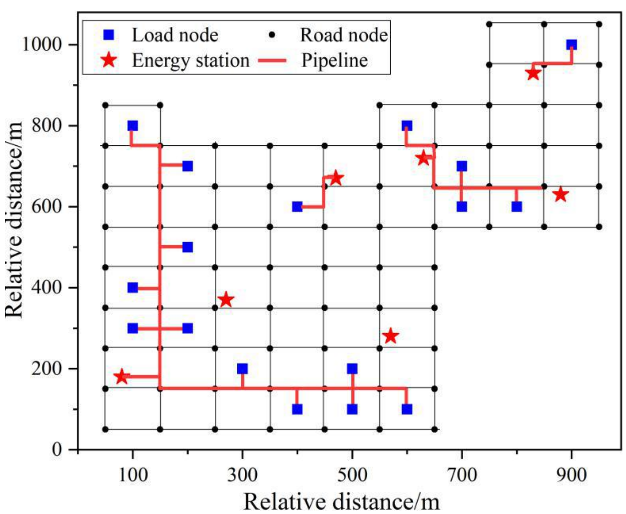

Figure 7: Optimal Layout of RES System Network

From the figure, it is evident that there are a total of four energy stations planned, with construction divided into two phases. The algorithm offers the optimal network path from all load areas to the designated energy stations, depicted by the red lines.

4. CONCLUSION

This paper introduces a dynamic energy station site selection and network layout optimization method that incorporates temporal analysis. Firstly, it determines the construction forms of energy stations and load allocations based on the DBSCAN algorithm. Typical scenarios are presented using a specific project as a backdrop to illustrate this method. Subsequently, an optimization model for the layout of a regional energy station system network is established, with the goal of minimizing the annual equivalent cost, in conjunction with the Floyd shortest path algorithm. Case studies have validated the rationality and feasibility of the proposed method. The method presented in this study enables a fully quantitative analysis of energy station planning and design, considering factors such as the number of energy stations, their locations, and network layouts. It facilitates the phased and dynamic construction of energy stations and networks, reducing initial project investment costs.

ACKNOWLEDGEMENT

This work was supported by The Carbon Emission Peak and Carbon Neutrality Innovative Science Foundation of Jiangsu Province "The key research and demonstration projects of future low-carbon emission buildings" (Grant No. BE2022606).

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