A Novel Method Based on the Graph Theory for Urban Energy Planning

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***Abstract*—In this work, a novel method to plan and optimize pathways mix of urban regional energy system is proposed. A general model with vertices, paths and network balance as the elements is established, the digraph is used to describe the energy conversion and management process visually. Then, the matrices describing the characteristics of the energy network are developed. Basing on it, the objective function corresponding to the energy conversion paths is assigned as the weight, in order to make a comparison of system performance of different pathways mix. Furthermore, a case study of cogeneration system is evaluated by using the developed mathematical model. The results reveal the energy saving characteristics in different scenarios, further illustrating the applicable conditions and optimal strategies of distributed energy system. It is indicated that the proposed methodology have the ability to ameliorate energy network at the process of new-built planning and built areas reconstruction.**

Keywords—energy planning; graph theory; urban regional energy; optimization

Symbols

DES	distributed energy system
CCHP	combined cooling, heating and power
COP	coefficient of performance
PGU	power generation units

Parameters

η_g	the power generate efficiency of the grid
η_e	the transmission efficiency of the grid
η_p	the power generation efficiency of the PGU
η_{rec}	the efficiency of recovery heat utilization of the PGU
η_b	thermal efficiency of the auxiliary boiler
η_h	the efficiency of the heat exchanger
COP_{ar}	the absorption coefficient of the absorption chiller
Q_e	the electrical load
Q_c	the cooling load
Q_h	the heating load

Variables

E_{grid}	the electricity purchased by the grid
F_{grid}	the fuel energy for the grid
E_{pgu}	the amount of power generated by the PGU
F_{pgu}	the fuel inputs for the PGU
F_b	the fuel inputs for the boiler
Q_{rec}	the recovery heat utilization of the PGU
Q_b	the heat generated by the boiler
Q_{c0}	the cooling capacity of the absorption chiller
Q_{h0}	the heat generated by the heat exchanger

I. INTRODUCTION

Climate change and global warming are the most serious environmental problems in late decades, which mainly originated by fuel-energy consumption of human activities [1,2]. However，urban energy system as an ecological node play an important role in addressing the climate change and environmental degradation. In fact, cities are responsible for more than 67% of the world's energy consumption and accounting for more than 70% of global CO_2 emissions [3,4]. Therefore, the main problem at present is to plan and optimize the urban energy network systematically, in order to reduce the negative effects caused by unreasonable energy consumption.

The primary challenge in energy systems is how to optimize the energy structure by considering environmental sustainability and efficient economic performances[5,6]. Research on the optimization of energy system has attracted considerable attention. Marzband et al. [7] constructed a microgrid energy management system based on mixed integer nonlinear programming to achieve maximum efficiency. This model has the ability to improve economic dispatch and reduce global power generation costs. Ahmed et al. [8] proposed a new energy planning methodology to reduce the cost of environmental constraints. This approach has a guiding role in reducing the total cost of electricity production. Topcu et al. [9] devoloped a energy analysis model based on the Promethee method to determine the power generation strategy. Combined with algorithm technology and robust analysis, the results show that the model can solve the problem of power generation planning. Oh et al. [10] applied an optimal planning method to discuss the relationship between the design parameter and economic feasibility. This method can be used as an important reference in cost oriented energy planning. Sajjad [11] proposed a holistic approach and decision-making tools to analyze the management process for the integration of various improvements options. The proposed methodology can be applicable to compare and evaluate various alternative technologies involved in improving the operation of power generation processes. Jing [12] carried out an integrated framework to address multi-objective optimization and multi-criteria evaluation of distributed energy system, the framework could be used to deal with optimal system design and dispatch strategy considering different objectives. Amir [13] introduced a model to minimize life cycle costs of meeting the energy demand by integrating cogeneration, solar and conventional energy sources. The output of the model have the ability to analysis the operating strategies and investment planning of the energy systems.

Other researchers put forward some energy planning theories with different objective for different geographical levels. Georgios [14] introduced an optimization framework for simultaneously planning of energy production and maintenance for cogeneration, the approach is a potential means for optimizing energy production and maintenance and enhancing the efficiency of the plant's energy allocation. Mehleri [15] proposed a mixed integer programming model for the design of distributed energy generation systems that meeting heating and power demand at the small neighborhood level. Li[16] developed a MILP model to optimize the economic and environmental performance of a distributed energy system coupled with regional energy networks, the method is of great significance to the operational strategy and evaluation indicators of DER systems at the neighborhood level. Huang[17] proposed a goal programming approach to calculate the energy planning indicators, it has the potential to conduct dynamic variation analysis of community energy flow more flexibly and reliably. Cumo et al.[18] introduced an approach for assessing and improving the energy flow from nature to the city. The approach demonstrates the urban cell energy balance through innovative technologies with the use of green resources for sustainable urban energy management. Huang [19] presented a community energy optimization model to optimize the heating system during the detailed planning stage. The conclusions show that using the proposed model is more effective than the community energy system dynamics model. Ren[20]have applied a bottom-up energy system optimization model to develop a local low-carbon society. The proposed model considered the operational strategies on cost minimization and emission minimization, it is a choice solution for energy management from both economic and environmental perspectives.

In the energy system analyses published in those literatures, the focus are mainly on partial analysis under the constraints of environmental and economic factors, the coordinated operation and optimal scheduling of multi energy flow are not considered enough. Moreover, the existed modeling methods have the disadvantage of lacking adequate visualisation tools during the construction and optimisation of the problem, which cannot intuitively reflect the energy flow relationship. Therefore, it is necessary to develop a more holistic approach to analyze the various components and processes of the energy system, this paper proposes a new method for planning an urban energy system to optimize the pathways mix of different levels energy network by using a general model.

II. Urban Regional Energy Planning Method

A. Introduction of Graph Theory

The graph theory is a branch of combinatorial mathematics, which has grown within the operation research and management science discipline. A directed graph is composed of a set of vertices $V=\{v_1,v_2,...\}$,a set of edges $E=\{e_1,e_2,...\}$,and a mapping Ψ that maps every edge onto some ordered pair of vertices (v_i,v_j). In a digraph, an edge is not only incident in a vertex on a vertex ,but is also incident outside the vertices and incident on the vertices.

The performance of physical systems depends not only on the characteristics of the components, but also on the relative position of the components [21]. A simple way to displaying the structure of a system is to draw a digraph consisting of points called "vertices" and a line segment called "edges" which connect these vertices, so that the vertices and edges have the ability to indicate the relationship between those components[22,23]. Graph theory has a very wide range of applications in engineering and sciences due to its inherent simplicity[24,25]. A graph can be used to represent almost any physical situation involving discrete objects and their coupling relationships.

B. Mathematical Model Based on the Graph Theory

With the advancement of energy system reform, the transition from traditional centralized energy system to distributed and sustainable energy system has become a trend[26].Various new energy utilization technologies provide a physical basis for multi-energy collaboration, thus, the most critical problem is to coordinate the overall layout of the energy network and configuring energy conversion vertex rationally.

Urban energy system is a complex network with multi-source multi-sink multi-path. To describe the urban energy conversion and management process, the definitions of port and branch are proposed based on the graph theory, the information exchange between components in the system can be described by a digraph. In the process of digraph modeling, the port is defined as the input or output port of the energy vertices with attributes, the branch is defined as a virtual energy flow from one output port of an energy vertex to one input port of another energy vertex, and the energy flow path is abstracted as the edge of the virtual network. In this way, the urban energy network can be visually analyzed.

Without loss of generality, the following definition are given to simplify the analysis. The energy network can be simplified into three parts: energy provide, energy transfer and energy demand. Energy provide is the inputting of energy such as fossil energy, renewable energy and electricity in the region. Energy transfer is the converting process between primary energy and secondary energy. Energy demand is the terminal loads of built environment, which are the basic resources to meet the needs of human activities. The general urban regional energy system model is shown in Fig.1, the definition of vertices are shown in Table 1.

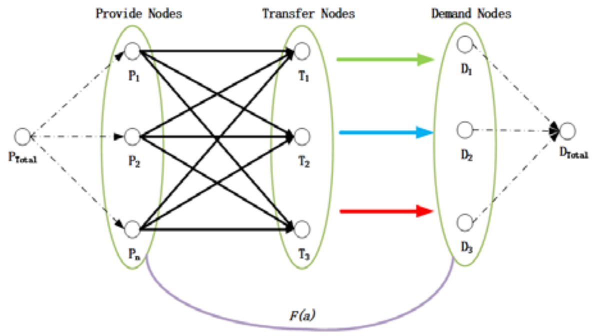


FIGURE I. THE GENERAL URBAN REGIONAL ENERGY SYSTEM MODEL

TABLE I. VERTICES LABELING AND REPRESENTATIVE MEANING

Vertex	Representative	Vertex	Representative	Vertex	Representative
P_1	Fossil energy	T_1	Power conversion	D_1	Electrical demand
P_2	Renewable energy	T_2	Cold conversion	D_2	Cooling demand
P_n	Others input	T_3	Heat conversion	D_3	Heating demand

In this section, a matrix modeling based on graph theory are introduced to describe the conversion and management process of the energy system, where the characteristics of energy pathways mix and their topology are expressed in matrix form. Combined with the energy system model described above, the source energy input combination matrix and the terminal energy output combination matrix are defined as:

$$P_{input} = [p_1 \quad p_2 \quad \cdots \quad p_i]^T \tag{1}$$

$$D_{input} = [D_1 \quad D_2 \quad \cdots \quad D_j]^T \tag{2}$$

The reachable matrix T is introduced to represent the energy conversion factors of the energy flow paths:

$$T = \begin{pmatrix} \eta_{P_1D_1} & \cdots & \eta_{P_1Dj} \\ \vdots & \ddots & \vdots \\ \eta_{P_iD_1} & \cdots & \eta_{P_iD_j} \end{pmatrix} \tag{3}$$

For the urban regional energy conversion and management system, the coupling between input energy sources and output energy sinks can be matrixed as:

$$\begin{bmatrix} D_1 \\ D_2 \\ D_j \end{bmatrix} = \begin{bmatrix} \eta_{P_1D_1} & \cdots & \eta_{P_1D_j} \\ \vdots & \ddots & \vdots \\ \eta_{P_iD_1} & \cdots & \eta_{P_iD_j} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_i \end{bmatrix} \tag{4}$$

Where P_i and D_j denote the n-th type of input energy source and the m-th type of output energy, respectively; $\eta_{P_iD_j}$ is the coupling factor with combination of the dispatch and efficiency, which means the energy pathways efficiency weight generated by different energy input vertices through different conversion vertices to meet the energy demand.

The objective function related to energy, environmental and economic factors is proposed to optimize the evaluation of the energy system.

$$f(\mathrm{E}) = \omega_1 f(E_1) + \omega_2 f(E_2) + \omega_3 f(E_3) \tag{5}$$

Where $f(E_1)$, $f(E_2)$, $f(E_3)$ are the sub-objective functions of energy flow, carbon emission, and economic cost, respectively. ω_1, ω_2, ω_3 are weighting factors, which indicate the degree of evaluation of energy indicators, environmental indicators, and economic indicators respectively, and the value ranges are all from 0 to 1. When performing a single objective function analysis on energy, economic, and environmental indicators, other sub-function weighting factors can be set as 0. When considering the energy-environment-economic multiple sectors, the weighting factors can be set by the analytic hierarchy process[27] to analyze and optimize different energy systems, which makes the model more flexible and versatile.

III. RESULT AND DISCUSSION

A. Energy Network Model of Cogeneration Systems

Cogeneration system have the potential to reduce energy consumption and carbon emission, it is widely recognized as a technical alternative method that can adjust the energy structure, improve energy efficiency, and ameliorate environmental pollution effectively[28-30]. However, whether the cogeneration system can fully utilize its advantages depends on the energy flow matching between supply and demand paths. In this discussion, the digraph modeling and the operational optimization of the cogeneration system are illustrated based on the developed mathematical model.

The comparative analysis of the energy flow process of the cogeneration system and the separation system are proposed, the digraph of energy network is shown in Fig.2 and the definition of vertices is shown in Table2. The left side is the cogeneration system energy flow network, T_2 as the power generation unit (PGU) is the core component of the system. The fuel is inputted into the PGU, which could generate high-grade electric and recovery heat as byproduct. The electric energy is used to power building, the insufficient part is suppled by the electric grid. The recovery heat is used to provide cooling and heating by absorption chillers and heat exchangers, the insufficient heat is attached by the auxiliary boiler. The right side is the separation system energy flow network, the power, heating and cooling load are suppled by the grid, the electric chiller and the gas boiler, respectively.

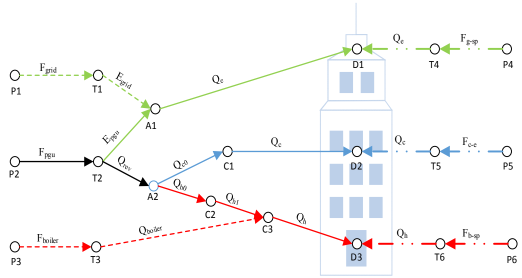


FIGURE II. THE ENERGY FLOW PROCESS OF THE COGENERATION SYSTEM AND THE SEPARATION SYSTEM

TABLE II. VERTICES AND THEIR SIGNIFICANCE

Vertex	Representative	Vertex	Representative	Vertex	Representative
				A1	Power junction
P1	Grid fuel	T1	Power plant	A2	Recovery heat
P2	PGU fuel	T2	PGU	C1	Absorption chiller
P3	Boiler fuel	T3	Auxiliary boiler	C2	Heat exchanger
P4	Sep-system grid	T4	Sep-system Power	C3	Heat junction
P5	Refrigerator power	T5	Refrigerator	D1	Electrical demand
P6	Sep-system boiler fuel	T6	Sep-system boiler	D2	Cooling demand
				D3	Heating demand

Combined with the network topology and vertices performance, the coulping characteristic can be matrixed as:

$$\begin{bmatrix} Q_e \\ Q_c \\ Q_h \end{bmatrix} = \begin{bmatrix} \eta_g & 0 & 0 \\ \eta_p & (1-\eta_p)\eta_{rec}\beta COP_{ar} & (1-\eta_p)\eta_{rec}(1-\beta)\eta_h \\ 0 & 0 & \eta_b \end{bmatrix} \begin{bmatrix} F_g \\ F_p \\ F_b \end{bmatrix} \quad (6)$$

The balance constraints for vertices and pathways in the energy flow network are shown in Table 3.

TABLE III. THE BALANCE CONSTRAINTS FOR VERTICES AND PATHWAYS

Vertices	Energy balance	Vertices	Energy balance
T1	$E_{grid} - F_{grid}\,\eta_e\eta_g = 0$	A2	$Q_{C0} + Q_{h0} = Q_{rec}$
T2	$E_{pgu} - F_{pgu}\,\eta_p = 0$		$Q_{C0} = \beta Q_{rev}$ $Q_{h0} = 1 - \beta Q_{rev}$
	$Q_{rec} - F_{pgu}(1-\eta_p)\eta_{rec} = 0$	C1	$Q_{c0}COP_{ar} - Q_c = 0$
T3	$Q_b - F_b\eta_b = 0$	C2	$Q_{h1} - Q_{h0}\eta_h = 0$
A1	$E_{pgu} + E_{grid} = Q_e$	C3	$Q_{h1} + Q_b = Q_h$
	$E_{grid} = (1-\alpha)Q_e$		$Q_{h1} = \gamma Q_h$ $Q_b = 1 - \gamma Q_h$

Where α is the share of the PGU's power generation in the total electric load; β is the share of the absorption chiller's cooling capacity in the total recovery heat utilization; γ is the share of the heat exchanger's heat generation in the total heating load.

In the section, the energy consumption is selected as the single objective function to analyze the system performance, and the objective function is assigned as the weight of the energy conversion paths. The objective function of the total energy consumption of the cogeneration system can be expressed as:

$$f(E) = F_{cchp} = \sum F_{pgu} + F_{grid} + F_b \quad (7)$$

The relative energy conservation rate of the cogeneration system is introduced as the objective function based on the system basic energy consumption:

$$f(a) = \frac{F_{sp} - F_{cchp}}{F_{sp}} \quad (8)$$

Where F_{sp}, F_{cchp} are the energy consumption of the cogeneration and separation system，respectively.

The design and operation of the CCHP system are dependent on the building environmental load characteristics, the load characteristics depend to a large extent on regional climate characteristics and building types[31,32]. In the model, two parameters ξ_1、ξ_2 are put forward to represent the ration of Q_h and Q_e, the ration of Q_c and Q_e respectively.

$$\xi_1 = \frac{Q_h}{Q_e} \quad (9)$$

$$\xi_2 = \frac{Q_c}{Q_e} \quad (10)$$

Combined with the equilibrium relationship model of each vertex, the energy conservation characteristics relationship between the cogeneration system and the separate system is derived as:

$$f(a) = 1 - \frac{\left[\alpha\eta_g\eta_b + (1-\alpha)\eta_p\eta_b + \xi_1\eta_p\eta_g - (1-\beta)\alpha(1-\eta_p)\eta_{rec}\eta_h\eta_g\right]cop}{\left[cop\,\eta_b + \xi_2\eta_b + \xi_1\eta_g cop\right]\eta_p} \quad (11)$$

The parameters values related to the energy flow network are set as shown in Table 4 [33-35].

The objective function can be expressed as:

$$f(a) = 1 - \frac{0.99\xi_1 + 1.9008\alpha\beta - 0.96\alpha + 2.4}{0.99\xi_1 + 0.98\xi_2 + 2.94} \quad (12)$$

TABLE IV. ENERGY FLOW NETWORK PARAMETER VALUES

System	Symbol	Variable	Value
Cogeneration system	η_g	Grid efficiency	0.33
	η_p	PGU efficiency	0.25
	η_{rec}	Waste heat recovery system efficiency	0.8
	η_b	Auxiliary boiler efficiency	0.98
	η_h	Heat exchanger efficiency	0.8
	COP_{ar}	Absorption chiller COP	1.2
Separate system	η_g	Grid efficiency	0.33
	COP	Refrigerator COP	3
	η_b	Boiler efficiency	0.98

B. Scenario Analysis

The (α, β), (ξ_1, ξ_2) as two sets of constraint variables of the heat source matching relationship and the terminal load parameters, which determining the energy conservation conditions of the cogeneration system. To evaluate the application performances of the system, three different scenarios are selected to compare in numerical analysis. The scenarios are as follows:

1) Case 1

The cooling load is much larger than the heating load, and cold is much larger than the heat amount the recovery heat utilization. Take β=0.7, $\xi_1:\xi_2$=3:7, the relationship of energy saving conditions is introduced as:

$$f(a) = 1 - \frac{0.99\xi_1 + 0.37056\alpha + 2.94}{3.277\xi_1 + 2.94} \tag{13}$$

2) Case 2

The heating load is much larger than the cooling load, and the heat is much larger than the cold amount the recovery heat utilization. Take β=0.3, $\xi_1:\xi_2$=7:3, the relationship of energy saving conditions is introduced as:

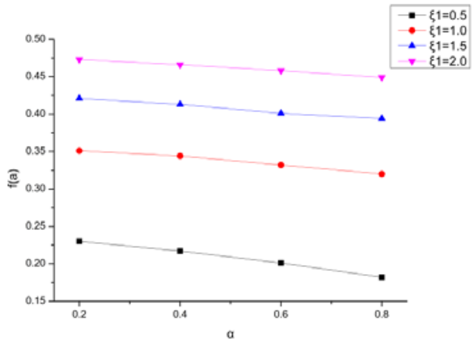
$$f(a) = 1 - \frac{0.99\xi_1 - 0.38976\alpha + 2.94}{1.41\xi_1 + 2.94} \tag{14}$$

3) Case 3

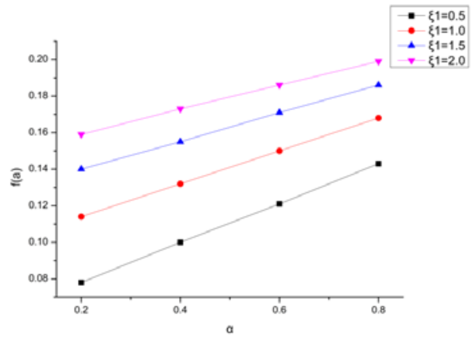
The cooling load is similar to the heating load, and the heat and cold amount the recovery heat utilization are almost the same. Take β =0.5, $\xi_1:\xi_2$ =1:1, the relationship of energy saving conditions is introduced as:

$$f(a) = 1 - \frac{0.99\xi_1 - 0.0096\alpha + 2.94}{1.97\xi_1 + 2.94} \tag{15}$$

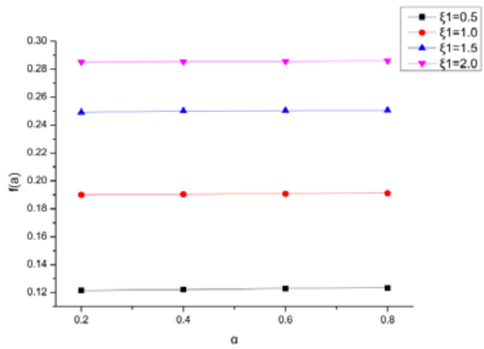
Different probabilistic PGU output quotas are selected as the parameter in the three scenarios, the system performance and trends with the various terminal thermoelectric ratio are shown in Fig.3



(a) case 1



(b) case 2



(c) case 3

FIGURE III. THE SYSTEM PERFORMANCE AND TRENDS WITH THE VARIOUS TERMINAL THERMOELECTRIC RATIO

As it can be seen from Fig.3, in the scenario of cooling dominates, the relative energy conservation rate of the cogeneration system decreases with the increase of the PGU output quota, and energy conservation rate is positively correlated with the terminal thermoelectric ratio when the same PGU output quota is used; In the scenario of heating dominates, the relative energy conservation rate of the cogeneration system increases with the increase of the PGU output quota, and energy conservation rate is positively correlated with the terminal thermoelectric ratio when the same PGU output quota is used; In the transition zone scenario, the relative energy conservation rate does not change significantly as the PGU output quota increase, and the relative energy conservation rate is positively correlated with the terminal thermoelectric ratio when the same PGU output quota is used.

C. Analysis and Discussion

The energy flow process of the cogeneration system is analyzed based on the proposed method, and the energy-saving condition of cogeneration system is derived. And then, the operation characteristics and applicable conditions are analyzed in a combination of qualitative and quantitative approach, the following conclusions are drawn:

(1) $(\alpha,\ \beta)$, $(\xi_1,\ \xi_2)$ as two sets of constraint variables of the heat source matching relationship and the terminal load parameters, which determining the energy conservation conditions of the cogeneration system.

(2) The energy conservation rate of the cogeneration system is positively correlated with the terminal thermoelectric ratio, indicating that sufficient and stable heating/cooling load is beneficial for the cogeneration system to exert its energy saving advantages. Because the high-grade natural gas resources is given priority to power generation, the generated waste heat can be fully utilized to meet the terminal heating/cooling load, which achieving the cascade utilization of energy and improving the comprehensive utilization efficiency.

(3) In different situations, the PGU output quota has different effects on the energy-saving characteristics of the cogeneration system. The relative energy conservation rate of the cogeneration system decreases with the increase of the PGU output quota in the scenario of cooling dominates, indicating that it is necessary to ensure that the PGU has sufficient thermal supply capacity to achieve low-grade energy cooling in this scenario area energy planning. However, in the scenario of heating dominates, the relative energy conservation rate of the cogeneration system increases with the increase of the PGU output quota, which means that it is significant to give full play to the high-grade natural gas, and reduce the proportion of high-grade energy heating in the construction of the energy system in this scenario.

IV. CONCLUSIONS

This work provides a novel energy planning method based on the graph theory to address the planning problem of urban energy network with multi-source, multi-sink and multi-path. A general model combining digraph and matrices is introduced to describe and optimize the urban energy conversion and management process visually. A case study of the cogeneration system is analyzed to determine the energy-saving characteristics and trends in different scenarios, the results show the optimal choice of the energy flow pathways, which has guidance for the promotion and utilization of regional energy system. The proposed methodology is appropriate for new-build planning and built areas reconstruction by optimizing path combination and promoting energy-saving technology.

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