Construction and analysis of a district heating / cooling network system based on thermal bus

T Xu¹, J Yan¹, H Wang², X L Wang¹, T Zhu² and H Y Wang²,³
¹Beijing Huajian Power Design and Research Institute, Beijing 102400, China
²School of Mechanical Engineering, Tongji University, Shanghai, 200092, China
E-mail: haiyingw@tongji.edu.cn

Abstract. A district energy system based on “thermal bus” was proposed, in which the heating and cooling water transmission processes shared one set of the distribution pipe network. Combined with the gas energy stations, ground source heat pumps, small-scale photovoltaic power stations and rooftop solar collectors and other facilities, it provided the users in the region with heating in winter, cooling in summer and power supply all year round. From the perspective of the bidirectional (supply/return) flow of heat energy along the thermal bus, the mathematical model of the main equipment applied for the source, pipe network, load and storage was established. The optimization model with the lowest system operation cost was proposed considering the fuel cost, the external electricity purchase fee and the satisfaction degree of all users’ energy demand. The operation cost and energy consumption of the regional energy system scheme and the traditional distributed energy system scheme are studied by a practical case study. The results showed that the new scheme reduces the operating cost by 21.5% and 16.8% respectively under the typical weekly scenarios of cooling in summer and heating in winter. When no storage equipment was used, the new scheme reduced the amount of purchased electricity in summer and winter by 4.1% and 5.2% respectively.

1. Introduction
The distributed energy systems have been increasingly applied in the regional comprehensive energy supply system by providing combined cold, heat and power supply (CCHP) [1,2]. However, a CCHP system with a single energy station can adapt to several buildings’ energy demand changes. When expanded to the district scale, a district distributed energy system (DDES) must be applied. To achieve high power generation, high thermal efficiency and high utilization rate, the DDES must have several interconnected energy stations and an adaptive energy distribution network to make full use of regional renewable energy, waste heat and other resources and to transfer the corresponding cooling, heating and electric energy from all energy stations to geographically scattered different kinds of buildings.

Several authors have investigated the role of transmission networks in optimizing the distributed energy systems [3-10]. Mehleri et al [3] proposed a mixed integer optimization model for the design and operation of a distributed energy system. And a district energy supply system was optimized combined with the heating network. Bracco et al [3] developed an optimized model for solving the energy supply of towns based on the cogeneration system. In the model, the heating network and the distributed energy were combined and used for the urban buildings, which reduced the annual cost and carbon dioxide emissions of the system. Yang et al [5] proposed an optimization model with the minimum cost of regional energy supply as the optimization target. The energy supply networks of
heating, cooling and power were integrated in the distributed energy system. And the strong coupling relationship between the supply side and the users’ side is partly eliminated by integrating the energy supply networks. Li et al [6] studied the economic and environmental optimization for distributed energy resource systems coupled with district energy networks, which also considered the equipment capacity of the energy supply network and the optimization of the network path. Jeddi et al [7] proposed a new modified harmony search algorithm to solve the proposed robust dynamic DER planning model. Van der Meer et al [8] and Mohamed et al [9,10] used the finite element method to model geothermal systems.

In district scale, however, to achieve the decoupling of the distributed energy systems and the energy distribution networks, some difficulties should be overcome: A variety of the power supply, heat and cold sources need to be merged in the energy system with their own special functions and features; Since multiple sources are connected to multiple users, the network may have the ability to provide energy from all sources to all users in an optimized way; It is necessary to consider how to reduce the temperature difference between the working fluid (water) and the environment to make full use of the pipe network and further reduce the loss of heating or cooling network.

Based on the configuration and operation mode of thermal bus, a new district comprehensive energy system is proposed in this paper. A mathematical model for the proposed system was established including the source, network, user’s load and energy storage. The combination of gas energy station, low-grade renewable energy and waste heat resources and various types of buildings were considered. The distributed variable-speed water pumps and the distributed heat pumps were used respectively to solve the hydraulic and thermal balance problems caused by the multiple heat/cold sources. Then, the performance of heating/cooling water distribution through the thermal bus, the utilization of low-grade energy and the reduction of network heat loss were studied. Furthermore, an optimization operation model was proposed to achieve optimal operation cost for the new comprehensive energy system, which was analyzed by a practical case.

2. Construction of the network system for cooling and heating
The configuration principle of the new regional thermal bus system in summer and winter is shown in figures 1(a) and 1(b) respectively. Water is used as the heating or cooling medium in the heating or cooling network, in which cascade utilization of energy should be the basic principle.
For a district scale, the proposed "thermal bus" configuration must be based on a ring-shaped topological network (including the supply and return water networks). The equalizing pipes should be arranged at each heat source [11]. The throttle valves and other equipment should be placed on the branch pipelines, which can be used only for local branch flow regulation. The water chillers or the heat pumps should be arranged in each building to further meet the cooling and heating load of each user in the building. However, unlike the traditional air conditioning units, the chillers inside each building in this energy system would exchange heat with the water supplied from the main network. The distributed heat pump can be also used to get the decoupling of the thermal transmission and distribution to achieve the thermal balance of the system. To achieve the hydraulic balance of the system, the distributed variable-speed water pumps should be adopted to get the decoupling of the hydraulic transmission and distribution.

In summer, the main network (as the bold line shown in figure 1(a)) provides cooling water to the buildings. The temperature of the cooling water is close to the temperature of the soil around the pipelines to reduce the heat loss, for instance 20°C. Inside each building, water chillers are used to provide chilled water to the users in each building. After passing through the water chillers, the cooling water will be heated to about 30°C and flow through the return water pipelines back into the energy station, the ground-source heat pump or the ice storage system to be cooled down before returning to the water supply pipelines.

In winter, the main network (as the bold line shown in figure 1(b)) provides low temperature heating water to the buildings, for instance 20°C. Inside each building, the heat pumps are used to provide the space heating and the domestic hot water (higher than 55°C). After passing through the heat pumps, the low temperature heating water will be cooled down to about 10°C and flow through the return water pipelines back into the energy station, the ground source heat pump or the solar collector to be heated before returning to the supply pipelines.

3. Models

3.1. Mathematical models

The model of a district integrated energy system mainly includes the sources, the network and the users. The sources are supposed to generate cold, heat and electricity energy, which might be the combined cooling heating and power station (CCHP), the gas-fired boilers, the renewable energy and the industrial waste heat. The network includes a power network, a gas pipe network and a cooling/heating pipe network. The users mainly refer to the buildings. In addition, the integrated energy system includes a variety of electrical, thermal or cold storage devices.

In the district integrated energy system, the source might be the gas turbines, the fuel cells, the gas boilers, the renewable energy and/or the waste heat resources etc. The thermodynamic model of each source may be complex and characteristic. While, for the energy network, each source can be simplified into a node model with only lumped parameters in order to conveniently fit the sources into the model of the network. When establishing the node model for a source, only its energy balance, hydraulic and thermal characteristics should be considered. The buildings can also be simplified as the node of energy using for the energy network, where the curve of heat load over time of the buildings can be obtained through simulation or measurement.

The district energy network includes the electric power network and the heating/cooling network. Through the power network, the energy stations, small solar photovoltaic and wind power stations can power the buildings in the area. The equivalent circuit of the cable transmission process in the power network is shown in figure 2. According to Zheng et al, the power loss in the transmission process can be calculated by the parameters such as voltage and phase angle [12], as shown in equation (1).

\[ W_{\text{grid}} = \sum_{k=1}^{K} g_k \left[ v_i^2 - v_j^2 - 2v_i v_j \cos(\theta_i - \theta_j) \right] \]  

(1)

Where, \( q_k \) is the equivalent conductance of the transmission cable \( k \), which connects the power.
transmission line \( i \) and line \( j \). \( V_i \) and \( \theta_i \) are the voltage and phase angle of the power transmission line \( i \) respectively. \( V_j \) and \( \theta_j \) are the voltage and phase angle of the power transmission line \( j \) respectively.

\[
R = R_{\text{equivalent resistance}}; \quad X = X_{\text{equivalent reactance}}; \quad B = B_{\text{equivalent capacitance}}; \quad V = V_{\text{voltage}}; \quad \theta = \theta_{\text{phase Angle}}; \quad i, j = \text{Power transmission lines}
\]

**Figure 2.** Equivalent circuit diagram of cable transmission network.

Modeling of the district heating and/or cooling system includes several kinds of the networks, such as the hot water heat-supply system, the steam heat-supply system and the cold supply system. Generally, the district heating and/or cooling system can be simplified into a network similar to a circuit according to the graph theory, and then based on the kirchhoff’s first and second laws, the node flow equilibrium equations and loop equations can be established [13-17].

### 3.2. Operational optimization model

The objective of operation optimization is to select the scheme with the lowest operation cost among all the feasible energy supply schemes for a certain energy system according to the predicted energy demands of the users. In the model, the proposed objective function considers the operating cost of all devices and meet the energy requirements of all users. The controllable variables in the energy system are the decision variables, such as the energy supply parameters of the power supply and the heat source, the degree of valve opening and the frequency control of the water pump. The constraint condition is the operating parameter ranges of all kinds of the energy supply/use equipment and the relation between the parameters.

The absolute value of the difference between the energy supplied and required is adopted as the indicator of the operation optimization in this paper. It can not only reflect the heat/cold loss of the network indirectly, but also show whether the system reaching its thermal equilibrium. The new indicator, \( GAP_H \) as shown in equation (2), is named as the satisfaction degree of the user’s heat/cold demand.

\[
Gap_H = \gamma \cdot \left[ \sum_{h=0}^{168} \sum_{n=1}^{N} |H_n - H_{n_{\text{need}}}| \right] \quad (2)
\]

Where, \( H_n \) is the actual heating/cooling energy supplied to the user \( n \); \( H_{n_{\text{need}}} \) is the required heating/cooling loads for the user \( n \); \( \gamma \) is the penalty factor, CNY/GJ. Larger \( \gamma \) means that the optimization model pays more attention to the user's satisfaction degree of heating/cooling; \( h \) is the serial number of the hours.

The objective function of operation optimization is defined as shown in equation (3),

\[
C_{\text{tot}} = \min \{ C_{\text{fuel}} + Gap_H \} \quad (3)
\]

Where, \( C_{\text{fuel}} \) is the total cost of the natural gas and electricity consumed by the sources; \( C_{\text{tot}} \) is the total operation cost.

For the nonlinear and strongly coupled energy system, intelligent optimization algorithm for global search, such as genetic algorithm (GA), should be adopted to do the optimization.

### 4. Case analysis
4.1. System planning

The planning Area of the Eco-Park is shown in figure 3. The planning area is in the central area, covering an area of about 0.57 km². The planned floor-space of the buildings in the central area is 1.83 km². According to the landform of the planning area and the location of the main users, three main heat sources are set. S1 is the gas-fired energy station with the gas-turbine generator set, the heat recovery boilers and the flue-gas absorption refrigeration units. S2 is the water source heat pump station with the double-pipe heat exchangers. S3 is the ground source heat pump station with air-cooled cooling tower. As shown in figure 4, in the district energy system, a ring-shaped pipe network and several branch pipes are arranged to connect the heat sources and the main users numbered from C1 to C13. For the power system planning, the gas-fired energy station is used as the main power source to supply electricity to the users in the region. In addition, PV solar panels are installed on the roof of the public venue buildings in the central area, serving as the auxiliary power supply to all buildings in the region through the local grid.

![Figure 3](image-url) Planning area of the eco-park, Zhenjiang, China.

![Figure 4](image-url) Topology of pipeline network.

The contrast of the integrated energy system based on thermal bus proposed in this paper with the traditional distributed energy system are shown in table 1.

| Season  | Item                                | Traditional distributed energy system          | Integrated energy system                      |
|---------|-------------------------------------|------------------------------------------------|------------------------------------------------|
| Year-round | Power supply mode                | Gas-fired energy station/PV                 | Gas-fired energy station /PV                     |
| Summer  | Supply/return water temperature   | Chilled water (7/12°C)                  | Cooling water (20/30°C)                         |
|         | Cooling equipment in the building | Air conditioner/coils                    | Chiller/air conditioner/coils                   |
|         | Domestic hot water equipment in the building | Solar collector/electric water heater        | Waste heat recovery heat pump/solar collector   |
|         | Cold storage                      | Water from a fire pool                   | Water in the main pipe network                  |
| Winter  | Supply/return water temperature   | High temperature hot water (70/40°C)       | Preheat the hot water (30/20°C)                 |
|         | Heating equipment in the building | Wall /floor radiator                     | Heat pump unit/radiator                         |
| Domestic hot water equipment in the building | Plate heat exchanger | Heat pump units |
|---------------------------------------------|---------------------|-----------------|
| Heat storage                                | None                | Water in the main pipe network |

4.2. Heating/cooling load
The users are numbered from C1 to C13 including a hotel, a hospital, a school, a railway station, a business area and some office/residential buildings etc. The typical weekly (168 h) heating, cooling and electricity loads of the users were calculated, as shown in figure 5. For the power system planning, the gas-fired energy station is used as the main power source to supply electricity to the users in the region. In addition, PV solar panels are installed on the roof of the public venue buildings in the central area, serving as the auxiliary power supply to all buildings in the region through the local grid.

![Figure 5](image)

**Figure 5.** Typical weekly (168 hours) heating, cooling and electricity loads of the user C1. (a) Heating load in winter, (b) Cooling load in summer and (c) Electricity Load.

4.3. Optimization calculation
The gas price was 2.26 CNY/Nm³. The electricity price was 0.5003 CNY/kWh. The penalty factor was 100.0 (CNY/GJ). Genetic algorithm (GA) was used to solve the model numerically. The solution flow of the model was shown in figure 6.

The difference in the calculation process of the traditional distributed energy planning approach and the approach presented were in step 2 and 4 in figure 6.

4.4. Results and analysis
The optimized parameters of the equipment in each energy station (S1, S2 and S3), the PV battery capacity and the parameters of the user’s heating/cooling equipment was calculated after the above solution process. Then according to the calculated optimal rated parameters, the equipment for three source and PV battery were selected as shown in tables 2 and 3. PV cells were set according to the building roof and open space area of the site.
1. Determine local climate and environmental parameters
2. Set pipe network topology and pipe size
3. Estimate the customer’s heating and cooling load
4. Set the rated parameters of the heat and power sources, set the operating range of the heat pump, chiller, heat exchanger, cooling tower and other equipment
5. Select the flow rate of a set of circulating pumps
6. Simulation of pipe network and power network
7. The simulation results are correct?
8. Operational optimization algorithm
9. Lowest cost?
10. Output unit design parameters and pump circulation flow, pressure distribution, etc

Figure 6. The solution flow of the model of the integrated energy system planning based on thermal bus.

Table 2. Parameters of the energy station equipment and photovoltaic cell.

| Station | Summer | Winter |
|---------|--------|--------|
|         | Rated parameter for electricity supply | Rated parameters for cooling supply | Rated parameters for heating supply |
|         | Power (kW) | Sets of equipment | Power (kW) | EER | Quantity | Power (kW) | EER | Quantity |
| S1      | 635     | 3       | 1116     | 1.3  | 3        | 1200     | 0.92 | 2        |
| S2      | -       | -       | 428.5    | 3.5  | 2        | 300      | 4.8  | 2        |
| S3      | -       | -       | 756.5    | 3.5  | 2        | 600      | 4.8  | 2        |
| PV      | 5.0     | 1200    | -        | -    | -        | -        | -    | -        |

Table 3. Parameters of the user’s equipment.

| SN | Summer | Winter |
|----|--------|--------|
|    | Water chiller | Heat pump for domestic hot water | Heat pump for heating | Heat pump for domestic hot water |
|    | Power (kW) | COP | Sets of equipment | Power (kW) | EER | Sets of equipment | Power (kW) | EER | Sets of equipment |
| C1 | 1407     | 3.6 | 2               | -          | -   | -               | -          | -   | -               |
| C2 | 176      | 3.5 | 2               | -          | -   | -               | -          | -   | -               |
| C3 | 1055     | 3.6 | 2               | -          | -   | -               | -          | -   | -               |
| C4 | 105.5    | 3.5 | 2               | -          | -   | -               | -          | -   | -               |
| C5 | 281.4    | 3.5 | 2               | -          | -   | -               | -          | -   | -               |
| C6 | 422.0    | 3.5 | 2               | 19.6       | 4.6 | 2               | 212.8      | 4.5 | 2               |
| C7 | 1055     | 3.6 | 2               | 47.3       | 4.6 | 2               | 502.2      | 4.8 | 2               |
| C8 | 562.7    | 3.5 | 2               | 24.0       | 4.6 | 2               | 303.6      | 4.5 | 2               |
| C9 | 492.4    | 3.5 | 2               | 21.2       | 4.6 | 2               | 303.6      | 4.5 | 2               |
Comparing the energy system proposed in this paper with the traditional distributed energy system, the total operating cost in a typical week was reduced by 21.5% in summer and 16.8% in winter. If using no storage equipment, the amount of purchased electricity of the new scheme was reduced by 4.1% in summer and 5.2% in winter. The purchased electricity required for the energy system proposed in this paper and the traditional distributed energy system, as shown in figure 7.

![Figure 7. Typical weekly costs for the thermal bus system and the traditional distributed energy system. (a) weekly operating costs and (b) weekly electricity purchased.](image)

5. Conclusions

An energy planning method based on thermal bus mode was proposed in this paper. In the district integrated energy system, different types and qualities of energy can be utilized in a more flexible way. The system can be used to improve the overall system energy efficiency, reduce investment and operating costs and fully meet the user's energy needs. The proposed pipe network can be used to distribute heating water in winter and cooling water in summer efficiently. The supply pipelines for heating are also the return pipelines for cooling. The low temperature of water in the supply/return pipes is beneficial for reducing the heat loss of the network and easily connecting the ground/water source heat pumps to the heating network. The operating costs can be saved and the electricity purchased from the grid can be reduced when using the proposed system.

References

[1] Cho H J, Smith A D and Mago P 2014 Combined cooling, heating and power: A review of performance improvement and optimization Appl. Energ. 136 168-85
[2] Liu M X, Shi Y and Fang F 2014 Combined cooling, heating and power systems: A survey Renew Sust. Energ. Rev. 35 1-22
[3] Mehleri E D, Sarimveis H, Markatos N C and Papageorgiou L G 2012 A mathematical programming approach for optimal design of distributed energy systems at the neighbourhood level Energy 44 96-104
[4] Bracco S, Dentici G and Siri S 2013 Economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area Energy 55 1014-24
[5] Yang Y, Zhang S and Xiao Y 2015 Optimal design of distributed energy resource systems coupled with energy distribution networks Energy 85 433-48
[6] Li L X, Mu H L, Li N and Li M 2016 Economic and environmental optimization for distributed energy resource systems coupled with district energy networks Energy 109 947-60
[7] Jeddi B, Vahidinasab V, Ramezanpour P, Aghaei J, Ahafie-khah M and Catalao J P S 2019 Robust optimization framework for dynamic distributed energy resources planning in distribution networks Int. J. Elec. Power 110 419-33
[8] Van der Meer F P, Al-Khoury R and Sluys L J 2009 Time-dependent shape functions for modeling highly transient geothermal systems Int. J. Numer. Meth. Eng. 77 240-60
[9] Mohamed M S, Seaid M, Trevelyan J and Laghouche O 2013 Time-independent hybrid enrichment for finite element solution of transient conduction–radiation in diffusive grey media J. Comput. Phys. 251 81-101
[10] Diwan G C, Mohamed M S, Seaid M, Trevelyan J and Laghouche O 2015 Mixed enrichment for the finite element method in heterogeneous media Int. J. Numer. Meth. Eng. 101 54-78
[11] Meng H, Wang H and Long W D 2017 District-energy planning method based on thermal bus system in hot summer and cold winter areas J. Refrig. 38 50-8 (In Chinese)
[12] Wang H, Wang H Y and Zhou H Z 2012 Analysis of multi-sources looped-pipe network based on object-oriented methodology J. Zhejiang Univ. (Eng. Sci.) 46 1900-9 (in Chinese)
[13] Wang H, Wang H Y and Zhu T 2017 A novel model for steam transportation considering drainage loss in pipeline networks Appl. Energ. 188 178-89
[14] Oppelt T, Urbanek T, Gross U and Platerz B 2016 Dynamic thermo-hydraulic model of district cooling networks Appl. Therm. Eng. 102 336-45
[15] Shaikh M M, Massan S R and Wagan A I 2015 A new explicit approximation to Colebrook’s friction factor in rough pipes under highly turbulent cases Int. J. Heat Mass. Tran. 88 538-43
[16] Lopes A M G 2004 Implementation of the hardy-cross method for the solution of piping networks Comput. Appl. Eng. Educ. 12 117-25
[17] Duquette J, Rowe A and Wild P 2016 Thermal performance of a steady state physical pipe model for simulating district heating grids with variable flow Appl. Energ. 178 383-93