Research on Design and Planning Method of Energy Internet Scenarios Under New-type Urbanization

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Abstract—In the general context of urbanization and energy transformation, energy development under new-type urbanization is faced with typical common issues such as a low share of clean energy, high energy intensity and high carbon intensity. To address these issues, this paper, focused on the design and planning method of scenarios in the energy interconnection systems under new-type urbanization, constructs the allocation of physical elements in the four aspects of energy supply, conversion, transmission and storage, establishes the architecture of energy interconnection systems and proposes a 1+N scenario construction method suitable for the diverse scenarios under new-type urbanization. In line with the energy development trends of interconnection, efficiency, low-carbon, digitization and diversification, this paper proposes a planning method of energy interconnection systems that adapts to diverse scenarios under new-type urbanization and verifies the proposed method with a practical computing example in a location. It provides valuable references for the construction of differentiated energy interconnection systems under new-type urbanization.

1. Introduction

Cities and towns are the core of energy supply and consumption. Since the reform and opening up, China has witnessed rapid urbanization. With increasing energy demand, energy security problems caused by heavy dependence on the import of oil, natural gas and other energy sources have brought a series of new problems and challenges to the urbanization development in China [1]. New-type urbanization, as its concept suggests, refers to the coordinated development and mutual promotion of small, medium, and large cities, small towns, and new rural communities [2]. Therefore, the construction of energy systems under new-type urbanization should be based on the basic guideline of green, low-carbon and sustainable development to improve the efficiency of energy utilization and fully leverage the natural advantages of renewable energy.

Under the macro constraints of energy transformation and the new urbanization strategy, urban energy systems will be stimulated to under great changes. With the deep integration of power energy and information technology and with the gradual maturity of market mechanisms, the future energy development under new-type urbanization will navigate in five directions: interconnection, efficiency, low-carbon, digitization and diversification [3]. Due to the lack of energy interconnection pathways, traditional urban energy systems struggle with problems such as low comprehensive energy efficiency, a low share of clean energy, and insufficient interaction between supply and demand [4]. At present, the energy Internet, which attracts the attention of experts and scholars at home and abroad, marks an important direction for the future energy development in China. With the aim to create a comprehensive service system for smart energy, an energy Internet ecosystem should be built to deeply integrate the Internet with the production, transmission, storage and consumption of energy and with the energy market, so that the resulting new development pattern of the energy industry is characterized by multi-energy coordination and open trading. This is an important technical solution to deal with the energy problems arising in the urbanization process of China [5-7]. At the same time, the resulting energy Internet technology under new-type urbanization is also an important part of the energy Internet ecosystem to promote the integration and unification of energy, information and business flows and to enhance the safe, economic and efficient use of energy in urban areas [8].

Planning is the basis for transforming energy interconnection systems from theory to practice, and it plays an important role in promoting the interconnection and close

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interaction of various energy sources [9]. At present, the energy interconnection systems under new-type urbanization are characterized by complex integrated modeling, multifaceted uncertainties, and frequent interactions between supply and demand sides. Traditional planning methods fail to provide comprehensive and coordinated planning of energy systems under new-type urbanization. Meanwhile, in order to ensure the efficient, reliable and stable operation of the energy interconnection systems, the characteristics mentioned above also pose challenges on the research and development of different energy coupling devices and of information and communication technology devices [10].

Therefore, this paper proposes the design and planning method of energy Internet scenarios under new-type urbanization, and verifies the proposed method with a practical example in a location. The rest of the paper is organized as follows: Section II describes the implication and basic architecture of the energy Internet under new-type urbanization and provides a 1+N scenario construction model for it; Section III introduces a modeling method of energy Internet planning that adapts to multiple scenarios under new-type urbanization; Section IV verifies the proposed method with a practical example in a location; Section V ends with the main conclusions.

2. Overview and Basic Architecture of Energy Internet under New-type Urbanization

2.1 Implication of the Energy Internet under New-type Urbanization

Urban energy Internet is a complex urban energy system with multiple network flows rooted in electric systems, based on the Internet and other cutting-edge information technologies, with distributed clean energy as the main primary energy sources, and closely coupled with other systems such as the natural gas network, the transportation network, and the heat/cooling supply network [11]. The supply side of the urban energy Internet includes not only primary energy sources but also distributed energy sources that have accessed, such as solar and wind energy; the transmission side must integrate a variety of industrial control and network information technologies to support efficient energy distribution; conversion is the essence of the energy Internet, and conversion between energy sources has gradually become a reality thanks to the development of technology, which is more favorable to the optimal distribution of energy. On the load application side, the access of active loads such as energy storage and electric vehicles results in load randomness and uncertainty - both temporally and spatially [12].

2.2 Architecture of Energy Internet under New-type Urbanization

The overall architecture of the urban energy Internet can be divided into a physical network layer of multi-energy interconnection, a support layer of energy information fusion, and a service layer of energy operation and management. As shown in Fig. 1, the physical network layer of multi-energy interconnection is a multi-energy network centered on power grids, with various forms of energy deeply integrated. It is strong in structure, flexible in operation, sharing and interactive, laying the material basis for the energy Internet under new-type urbanization. The support layer of energy information fusion is an energy communication network covering the urban energy systems in all the regions and fields, with high bandwidth, high speed, high reliability and high compatibility, providing intelligent support for the energy Internet under new-type urbanization. The service layer of energy operation and management is a comprehensive energy service management platform covering various energy sources in cities to realize the horizontal interaction between different energy systems and the vertical interaction between energy service providers and users, acting as a service management hub for energy Internet under new-type urbanization.

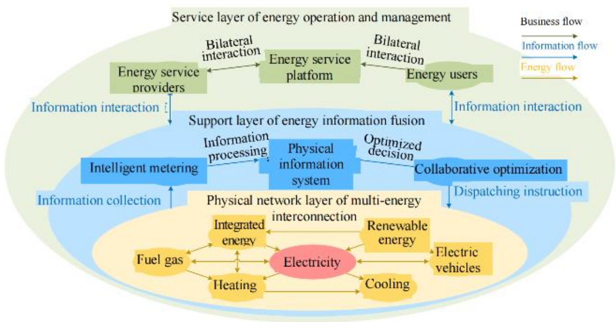

Figure 1. Architecture of Energy Internet under New-type Urbanization

2.3 1+N Scenario Construction Model in Energy Internet under New-type Urbanization

“1” represents the energy supply-demand relationship under new-type urbanization that is unique. The urban energy supply-demand relationships include energy input, energy output, and energy self-balance. For specific new-type cities and towns, the unique supply-demand relationship depends on the energy resource endowment, different power sources and energy consumption.

“N” represents the energy demand characteristics of each functional cluster in new-type cities and towns. For example, a city or a town may be divided by industrial orientation into residential, commercial, industrial, logistics and many other functional zones each of which has different energy consumption characteristics. Specifically, southern and northern residential areas as well as commercial areas may be differed in energy consumption. The energy consumption characteristics in the industrial zone can be classified by industrial types. An urban energy interconnection system can be planned as a cluster of individual functional zones or as a multi-functional cluster or a random cluster.

For example, for the purpose of planning the energy Internet system in a town, the local energy supply-demand relationship is assessed and analyzed and it is concluded that this is an energy input town that meets residential, commercial and industrial energy demand in the north. According to the “1+N” scenario construction model, the town falls into the scenario of “residential, commercial and industrial clusters in the north based on energy input”.

3. Modeling of Energy Internet Planning under New-type Urbanization

In order to build a clean, low-carbon, safe and efficient modern energy system, the objective function of the model is set as a comprehensive optimum of economic, environmental, energy efficiency and electrification rate objectives, and the weight factors of the objectives are balanced against the practical development needs of the planned region, taking into account the localized development focus while seeking comprehensive development. The economic objective is to minimize the total investment and the total operating cost; the environmental objective is to minimize the total carbon dioxide emissions; the energy efficiency objective is to maximize the total energy efficiency of the system; and the electrification rate objective is to maximize the proportion of electric energy in the planned region.

3.1 Objective Function

3.1.1 Economic Objective: To Minimize the Total Investment and the Total Operating Cost of the Energy Interconnection System

$$\min F = C_{INV} + C_{OPE} \tag{1}$$

In which: C_{INV} is the total investment cost, and C_{OPE} is the total operating cost.

3.1.1.1 Investment Cost

The investment cost includes the average annual construction cost of alternative lines for the electricity, gas, and heating subsystems, the average annual construction cost of alternative equipment in the energy conversion process, and the average annual construction cost of distributed power and energy storage equipment.

$$\begin{aligned} C_{INV} = & \sum_{(i,j)\in\Omega_{EL}} x_{ij}^{EL} C_{ij}^{EL} + \sum_{(i,j)\in\Omega_{GL}} x_{ij}^{GL} C_{ij}^{GL} + \sum_{(i,j)\in\Omega_{HL}} x_{ij}^{HL} C_{ij}^{HL} \\ & + \sum_{k\in\Omega_{EnH}} x_k^{EnH} C_k^{EnH} + \sum_{l\in\Omega_{DG}} x_l^{DG} C_l^{DG} + \sum_{m\in\Omega_{ES}} x_m^{ES} C_m^{ES} \end{aligned} \tag{2}$$

In which: Ω_{EL}, Ω_{GL}, Ω_{HL} and Ω_{EnH} are the sets of alternative lines for the power distribution network, the natural gas subsystem and the heating subsystem and the set of alternative equipment in the energy hub, respectively; x_{ij}^{EL}, x_{ij}^{GL} and x_{ij}^{HL} are the token 0-1 variables of alternative lines between nodes in the power distribution network, the natural gas subsystem and the heating subsystem, respectively, 0 for no alternative line while 1 for the availability of alternative lines; C_{ij}^{EL}, C_{ij}^{GL} and C_{ij}^{HL} are the average annual construction costs of the alternative lines between Node *i* and Node *j* in the power distribution network, the natural gas subsystem and the heating subsystem, respectively; x_k^{EnH} is the token 0-1 variable of certain alternative energy conversion equipment in the energy hub, 0 for no alternative equipment while 1 for the availability of alternative equipment; C_k^{EnH} is the average annual construction costs of each alternative equipment for energy conversion, including: gas generator (GG), combined heat and power (CHP), combined cooling, heat and power (CCHP), gas boiler (GB), electric heater (EH), heat pump (HP), electric cooler (EC), absorption chiller (AC) and power-to-gas (P2G). Ω_{DG} and Ω_{ES} are the sets of alternative distributed power sources and the set of alternative energy storage, respectively; x_l^{DG} and x_m^{ES} are the token 0-1 variables of alternative distributed power sources and alternative energy storage, respectively, 0 for no alternative distributed power source and alternative energy storage while 1 for the availability of alternative distributed power source and alternative energy storage; C_l^{DG} and C_m^{ES} are the average annual construction costs of the corresponding distributed power source and energy storage equipment, respectively.

3.1.1 2 Operating Cost

The operating cost includes the cost of purchased electricity for the power distribution network, the cost of purchased gas for the gas distribution network, the cost of purchased heat for the heat distribution network, and the incentive cost of demand response.

$$C_{OPE} = \sum_s \sum_t \begin{pmatrix} \lambda_e \sum_{i\in\Omega_{esta}} SP_i^{E,ts} + \lambda_g \sum_{i\in\Omega_{gsta}} SP_i^{G,ts} + \lambda_h \sum_{i\in\Omega_{hsta}} SP_i^{H,ts} \\ +\mu_{drp} \sum_{i\in\Omega_{drp}} P_i^{drp,ts} + \mu_{drh} \sum_{i\in\Omega_{drh}} P_i^{drh,ts} + \mu_{drc} \sum_{i\in\Omega_{drc}} P_i^{drc,ts} \end{pmatrix} \tag{3}$$

In which: Ω_{esta}, Ω_{gsta} and Ω_{hsta} are the sets of substations, gas distribution stations and heat distribution stations, respectively; $SP_i^{E,ts}$, $SP_i^{G,ts}$ and $SP_i^{H,ts}$ are the energy purchased from the substations, gas distribution stations and heat distribution stations at *t* (hour) in *s* (season), respectively; λ_e, λ_g and λ_h are the unit prices of the purchased electricity, gas and heat, respectively. Ω_{drp}, Ω_{drh} and Ω_{drc} are the sets of electricity nodes, heat energy nodes and cooling energy nodes with demand response potential, respectively; $P_i^{drp,ts}$, $P_i^{drh,ts}$ and $P_i^{drc,ts}$ are the electric power, the heat power and the cool power at which the demand response is reduced at *t* (hour) in *s* (season), respectively; μ_{drp}, μ_{drh} and μ_{drc} are the unit incentive coefficients of electric, heating and cooling demand response, respectively.

3.1.2 Environmental Objective: To Minimize the Total Carbon Dioxide Emissions

$$\min F_{EN} = \sum_t (\rho_{CO2}^{GB} PG_i^{GB,t} + \rho_{CO2}^{GG} PG_i^{GG,t} + \rho_{CO2}^{CHP} PG_i^{CHP,t} + \rho_{CO2}^{CCHP} PG_i^{CCHP,t}) \tag{4}$$

In which: $PG_i^{GB,t}$, $PG_i^{GG,t}$, $PG_i^{CHP,t}$ and $PG_i^{CCHP,t}$ are the power of GB, GG, CHP and CCHP at *t*, respectively; ρ_{CO2}^{GB}, ρ_{CO2}^{GG}, ρ_{CO2}^{CHP} and ρ_{CO2}^{CCHP} are the proportionality coefficients of the power of GB, GG, CHP and CCHP to carbon dioxide emissions, respectively.

3.1.3 Energy Efficiency Objective: To Maximize the Total Energy Efficiency of the System

$$\min F_{EF} = \sum_{i\in\Omega_{esta}/\Omega_{gsta}/\Omega_{hsta}} \frac{LP_i^{E,ts} + LP_i^{G,ts} + LP_i^{H,ts} + LP_i^{C,ts}}{SP_i^{E,ts} + SP_i^{G,ts} + SP_i^{H,ts}} \tag{5}$$

In which: $SP_i^{E,ts}$, $SP_i^{G,ts}$ and $SP_i^{H,ts}$ are the energy purchased from the substations, gas distribution stations and heat distribution stations at *t* (hour) in *s* (season), respectively, and $LP_i^{E,ts}$, $LP_i^{G,ts}$, $LP_i^{H,ts}$ and $LP_i^{C,ts}$ are the electric, gas, heat, and cool energy consumed by users at *t* (hour) in *s* (season), respectively.

3.1.4 Electrification Rate Objective: To Meet the Required Proportion of Electric Energy

$$\min F_{EF} = -\frac{SP_i^{E,ts}}{SP_i^{E,ts} + SP_i^{G,ts} + SP_i^{H,ts}} \tag{6}$$

In which: $SP_i^{E,ts}$, $SP_i^{G,ts}$ and $SP_i^{H,ts}$ are the energy purchased from the substations, gas distribution stations and heat distribution stations at *t* (hour) in *s* (season), respectively.

3.2 Constraints

The constraints for the planning model of the energy interconnection system under new-type urbanization can be divided into three categories based on the functional modules: energy conversion constraint, energy storage constraint, and energy transmission constraint. Each module is an integral part of the energy interconnection system under new-type urbanization, covering the operating constraints in the whole chain of power supply, grid, load and energy storage and various types of equipment. The energy conversion constraints mainly include the constraint of cooling, heat and electric power balances in the energy hub, the capacity constraint of equipment in the energy hub and the distributed power constraint. The energy storage constraint is mainly the power balance constraint constructed on the basis of the functional characteristics of storage devices. The energy transmission constraints mainly include the power balance constraints, transmission capacity constraints, and demand response characteristics of the distribution network, the gas distribution network and the heat distribution network.

3.2.1 Energy Conversion Devices Constraints

3.2.1.1 Constraint of Cooling, Heat and Electric Power Balances in Energy Hub

$$\begin{cases} LP_i^{C,ts} = \eta_i^{EC} P_i^{E,EC,ts} x_{i,EC}^{EnH} + \eta_i^{AC} P_i^{H,AC,ts} x_{i,AC}^{EnH} \\ \quad + \eta_i^{CCHP} P_i^{G,CCHP,ts} x_{i,CCHP}^{EnH} \\ LP_i^{H,ts} = \eta_i^{GB} P_i^{G,GB,ts} x_{i,GB}^{EnH} + \eta_i^{CHP,H} P_i^{G,CHP,ts} x_{i,CHP}^{EnH} \\ \quad + \eta_i^{CCHP,H} P_i^{G,CCHP,ts} x_{i,CCHP}^{EnH} + \eta_i^{EH} P_i^{E,EH,ts} x_{i,EH}^{EnH} \\ \quad + \eta_i^{HP} P_i^{E,HP,ts} x_{i,HP}^{EnH} \\ LP_i^{E,ts} = \eta_i^{GG} P_i^{G,GG,ts} x_{i,GG}^{EnH} + \eta_i^{CHP,E} P_i^{G,CHP,ts} x_{i,CHP}^{EnH} \\ \quad + \eta_i^{CCHP,E} P_i^{G,CCHP,ts} x_{i,CCHP}^{EnH} \\ LP_i^{G,ts} = \eta_i^{P2G} P_i^{G,P2G,ts} x_{i,P2G}^{EnH} \end{cases} \tag{7}$$

In which: $LP_i^{C,ts}$, $LP_i^{H,ts}$, $LP_i^{E,ts}$ and $LP_i^{G,ts}$ are the cooling load, heat load, electric load and gas load of the energy hub *i* at *t* (hour) in *s* (season), respectively; $P_i^{E,EC,ts}$ and η_i^{EC} are the input electric power of the electric cooler in the energy hub *i* at *t* (hour) in *s* (season) and the efficiency of the electric cooler to convert electric energy into cooling energy, respectively; $x_{i,EC}^{EnH}$ is the token 0-1 variable of the electric cooler, 0 for no electric cooler while 1 for availability of the electric cooler. The variables for the other equipment are similar and not repeated herein.

3.2.1.2 Capacity Constraint of Equipment in Energy Hub

$$\begin{cases} 0 \le \eta_i^{GG} P_i^{G,GG,ts} \le P_i^{GG\max} x_{i,GG}^{EnH} \\ 0 \le (\eta_i^{CHP,H} + \eta_i^{CHP,E}) P_i^{G,CHP,ts} \le P_i^{CHP\max} x_{i,CHP}^{EnH} \\ 0 \le (\eta_i^{CCHP,H} + \eta_i^{CCHP,E} + \eta_i^{CCHP,C}) P_i^{G,CCHP,ts} \le P_i^{CCHP\max} x_{i,CCHP}^{EnH} \\ 0 \le \eta_i^{GB} P_i^{G,GB,ts} \le P_i^{GB\max} x_{i,GB}^{EnH} \\ 0 \le \eta_i^{EH} P_i^{E,EH,ts} \le P_i^{EH\max} x_{i,EH}^{EnH} \\ 0 \le \eta_i^{HP} P_i^{E,HP,ts} \le P_i^{HP\max} x_{i,HP}^{EnH} \\ 0 \le \eta_i^{EC} P_i^{E,EC,ts} \le P_i^{EC\max} x_{i,EC}^{EnH} \\ 0 \le \eta_i^{AC} P_i^{H,AC,ts} \le P_i^{AC\max} x_{i,AC}^{EnH} \\ 0 \le \eta_i^{P2G} P_i^{E,P2G,ts} \le P_i^{P2G\max} x_{i,P2G}^{EnH} \end{cases} \tag{8}$$

In which: $P_i^{GG\max}$, $P_i^{CHP\max}$, $P_i^{CCHP\max}$, $P_i^{GB\max}$, $P_i^{EH\max}$, $P_i^{HP\max}$, $P_i^{EC\max}$, $P_i^{AC\max}$ and $P_i^{P2G\max}$ are the maximum output energy of GG, CHP, CCHP, gas turbine, EH, HP, EC, AC and P2G in the energy hub *i*, respectively.

3.2.1.3 Distributed Power Constraint

$$0 \le P_i^{DG,ts} \le \sigma_i^{DG,ts} P_i^{DG\max} x_i^{DG} \tag{9}$$

In which: $P_i^{DG\max}$ is the maximum active power output by the distributed power source at Node *i*, and $\sigma_i^{DG,ts}$ is the output coefficient of the distributed power source at *t* (hour) in *s* (season).

3.2.2 Energy Storage Device Constraint

$$P_i^{ES,n} = P_i^{ESout,n} - P_i^{ESin,n} \tag{10}$$

$$SOC_i^{n+1} = SOC_i^n + \varepsilon_i^{loss} P_i^{ESin,n} - P_i^{ESout,n} \tag{11}$$

$$SOC_i^0 = SOC_i^N \tag{12}$$

$$-P_i^{ES\max} x_i^{ES} \le P_i^{ES,n} \le P_i^{ES\max} x_i^{ES} \tag{13}$$

$$0 \le P_i^{ESin,n} \le P_i^{ES\max} x_i^{ES} \tag{14}$$

$$0 \le P_i^{ESout,n} \le P_i^{ES\max} x_i^{ES} \tag{15}$$

$$SOC_i^{\min} \le SOC_i^n \le SOC_i^{\max} \tag{16}$$

In which: *n* is a time period, and *N* is the total number of time periods in a dispatching cycle which is 24h in a day. $P_i^{ES,n}$ is the net energy discharge power; $P_i^{ESin,n}$ is the energy charge power; $P_i^{ESout,n}$ is the energy discharge power; SOC_i^n is the stored energy; ε_i^{loss} is the energy loss rate during charging.

3.2.3 Energy Transmission Grid Constraints

3.2.3.1 Power Distribution Network Constraints

① Node Balance Constraint

$$\sum_{(i,j)\in\Omega_{GL}} P_{ji}^{G,ts} + SP_i^{G,ts} = \sum_{(i,k)\in\Omega_{GL}} P_{ik}^{G,ts} + LP_i^{G,ts} + P_i^{G,ts} \tag{17}$$

In which: $P_{ik}^{G,ts}$ is the energy distributed by the gas distribution network *ik* at *t* (hour) in *s* (season); $SP_i^{G,ts}$ is the energy injected from the gas distribution station to Node *i* at *t* (hour) in *s* (season); $LP_i^{G,ts}$ is the gas load at Node *i* of the gas distribution network at *t* (hour) in *s* (season); $P_i^{G,ts}$ is the energy input into the energy hub from the gas distribution network at *t* (hour) in *s* (season).

② Gas Distribution Pipe Capacity Constraint

$$0 \le P_{ij}^{G,ts} \le P_{ij}^{G\max} x_{ij}^{GL} \tag{18}$$

In which: $P_{ij}^{G\max}$ is the maximum energy transmitted by the gas distribution pipe *ij*.

③ Gas Distribution Station Output Constraint

$$0 \le SP_i^{G,ts} \le SP_i^{G\max} \tag{19}$$

In which: $SP_i^{G\max}$ is the maximum energy input to Node *i* of the gas distribution network.

3.2.3.2 Heat Distribution Network Constraints

① Node Heat Balance Constraint

$$\sum_{(i,j)\in\Omega_{HL}} P_{ji}^{H,ts} + SP_i^{H,ts} = \sum_{(i,k)\in\Omega_{HL}} P_{ik}^{H,ts} + LP_i^{H,ts} + P_i^{H,ts} - P_i^{DR,h,ts} \tag{20}$$

In which: $P_{ik}^{H,ts}$ is the heat transmitted by the heat distribution network pipe *ik* at *t* (hour) in *s* (season); $SP_i^{H,ts}$ is the heat injected into Node *i* from the heat distribution station at *t* (hour) in *s* (season)*s*; $LP_i^{H,ts}$ is the heat load at Node *i* in the heat distribution network at *t* (hour) in *s* (season); $P_i^{H,ts}$ is the heat input into the energy hub from the heat distribution network at *t* (hour) in *s* (season); $P_i^{DR,h,ts}$ is the heat power for demand response reduction at *t* (hour) in *s* (season).

② Heat Distribution Pipe Capacity Constraint

$$0 \le P_{ij}^{H,ts} \le P_{ij}^{H\max} x_{ij}^{HL} \tag{21}$$

In which: $P_{ij}^{H\max}$ is the maximum energy transmitted by the heat distribution pipe *ij*.

③ Heat Distribution Station Output Constraint

$$0 \le SP_i^{H,ts} \le SP_i^{H\max} \tag{22}$$

In which: $SP_i^{H\max}$ is the maximum heat output by the heat distribution station at Node *i*.

④ Demand Response Constraint

$$0 \le P_i^{DR,h,ts} \le (P_i^{DR,h,ts})_{\max} \tag{23}$$

In which: $(P_i^{DR,h,ts})_{\max}$ is the maximum heat power for demand response at Node *i*.

3.3 Model Solution Process

The solution process of the multi-objective optimal programming model built for the energy interconnection system under new-type urbanization in this section is shown in Fig. 2. The model is built with the YALMIP language, transformed into a mixed integer linear programming model suitable for solution through linearization of the nonlinear model, and solved on MATLAB 2017b with the commercial Cplex solver.

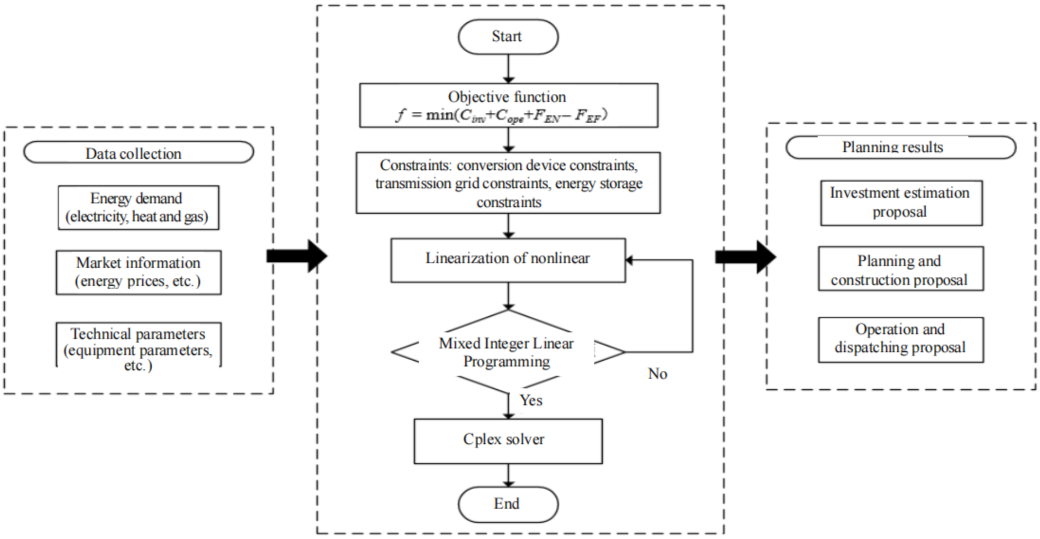

Figure 2. Solution Process of the Overall Planning Model

4. Example Test

4.1 Setting of Background Parameters in the Example

According to the definition of the “1+N” scenarios, “N” in the example is set as a functional cluster of “residential, commercial and industrial areas” where the energy consumption characteristics in the residential area are consistent with the basic characteristics in southern cities. Different scenarios are set according to the abundance of external gas and power supplies. When the external gas supply is insufficient but the local gas supply is abundant and the local power supply is sufficient, the condition for exporting energy is met. In this case, the scenario is defined as energy output. When the external gas supply is limited and the external power supply is insufficient but the local power supply is sufficient, power energy is considered as the main local energy and sufficient. In this case, the scenario is defined as energy self-balance, as shown in Table 1.

Table 1 External Power and Gas Supply Capacity by Scenario

Scenario Setting	External Power Supply Capacity	External Gas Supply Capacity	Type of Energy Supply Scenario	Type of Energy Consumption Scenario
Scenario 1	Abundant	Abundant	Energy input	Residential, commercial and industrial areas
Scenario 2	Abundant	Short external supply, but local abundant supply	Energy output	Residential, commercial and industrial areas
Scenario 3	Short external supply, but local abundant supply	Moderate	Energy self-balance	Residential, commercial and industrial areas

As shown in Fig. 3, the example is composed of an IEEE 30-node power distribution network system, a 7-node gas distribution network system, and a 6-node heat distribution network system. In the example, the fixed electricity price is RMB 0.6/kW·h, the natural gas price is RMB 3/m3, the purchased heat price is RMB 25/kW·h, and the construction cost of the alternative lines for the fixed power distribution network system is RMB 100,000/line.

The loads in the IEEE 30-node power distribution network system are divided into loads in residential, commercial and industrial areas, while taking into account the access of EV charging piles. The typical daily curves of electricity loads are shown in Fig. 4, Fig. 5, Fig. 6 and Fig.7. The setting is that the typical days account for 360 dispatching cycles (one day for one dispatching cycle) in a year, and the typical days in each of the spring, summer, autumn and winter account for 90 dispatching cycles. The gas and heat load curves for each typical day are shown in Fig. 8 and Fig. 9, in which the gas and heat load curves for typical days in spring and autumn are integrated as one curve for the convenience of calculation because they are relatively similar. The unit investment cost and conversion efficiency of the equipment, as well as the unit investment and construction cost of the energy storage devices in the energy interconnection system are shown in Table 2, Table 3 and Table 4, respectively.

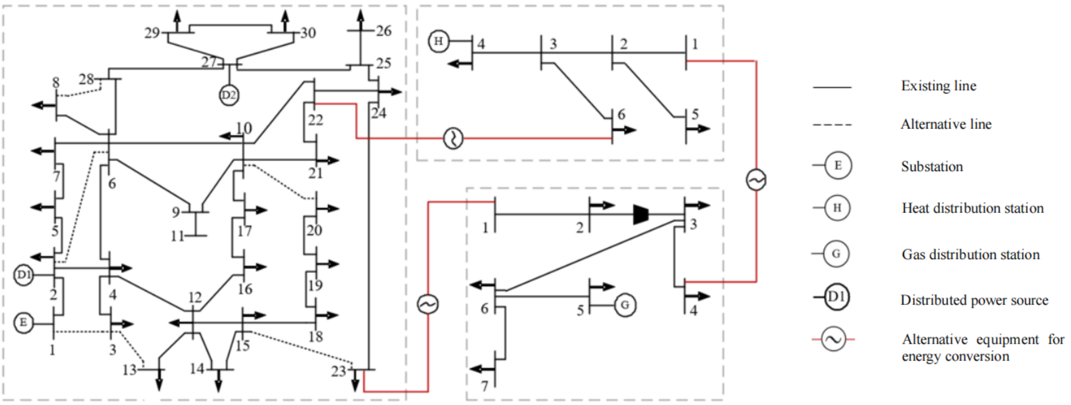

Figure 3. IEEE 30-Node Power Distribution Network - 7-Node Gas Distribution Network - 6-Node Heat Distribution Network Systems

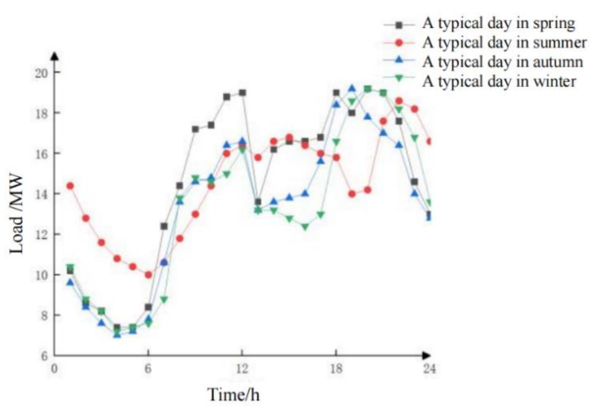

Figure 4. Electricity Load Curves of Typical Days in Residential Area

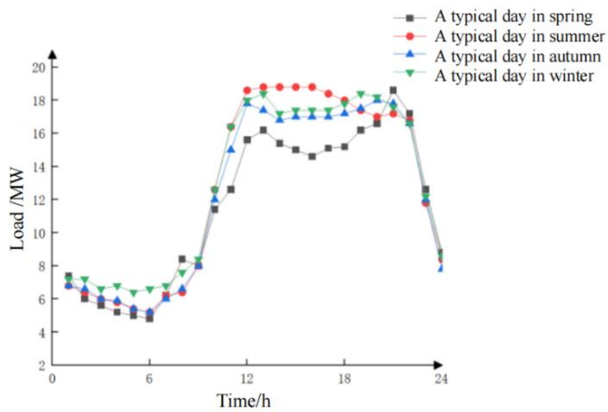

Figure 5. Electricity Load Curves of Typical Days in Commercial Area

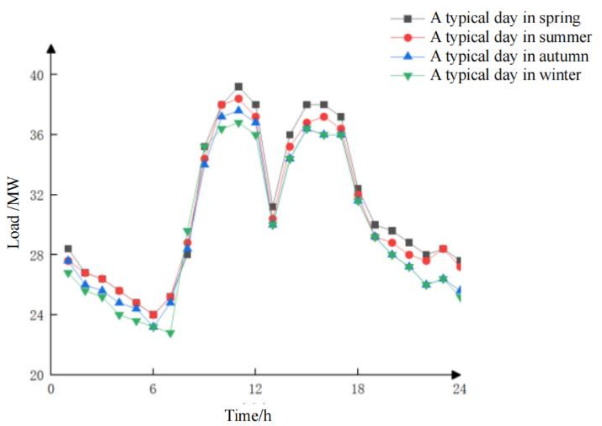

Figure 6. Electricity Load Curves of Typical Days in Industrial Area

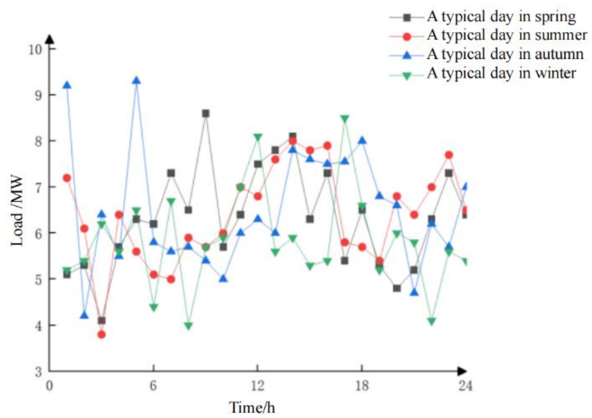

Figure 7. Electricity Load Curves of Typical Days with EV Charging Piles

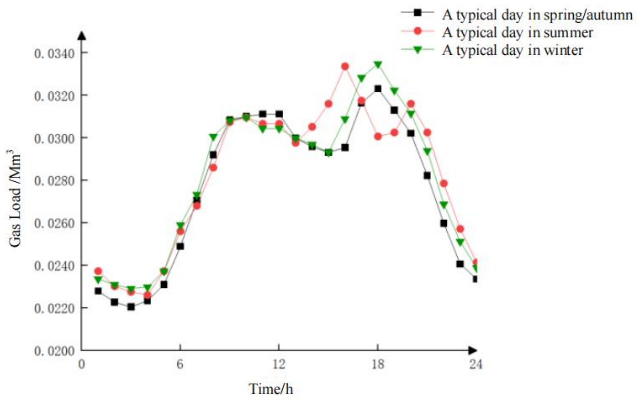

Figure 8. Gas Load Curves of Typical Days

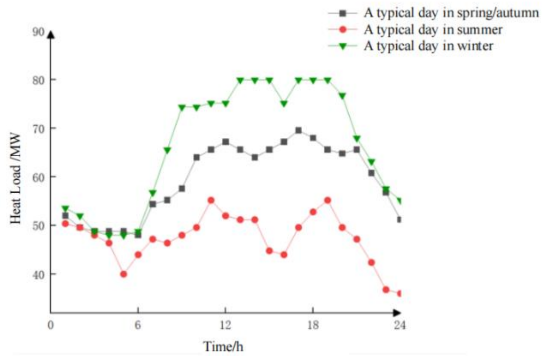

Figure 9. Heat Load Curves of Typical Days

Table 2 Unit Investment Cost of Conversion Equipment (Unit: RMB/kW)

Type	GB	GG	CHP	CCHP	EH	HP	P2G	PV Power Generation	Wind Power Generation
Investment Cost	1700	6500	6000	9800	3000	1000	3500	6500	7500

Table 3 Parameter Settings of Conversion Equipment

Type	GB	GG	CHP		CCHP		EH	HP	P2G
			η_{CHP}^{e}	η_{CHP}^{h}	η_{CCHP}^{e}	η_{CCHP}^{h}			
Conversion efficiency	0.85	0.3	0.4	0.45	0.4	0.4	3.2	3	0.7

Table 4 Unit Investment Cost of Energy Storage Equipment (Unit: RMB/kW)

Type	Power Storage	Gas Storage	Heat Storage
Investment cost	200	3.33	100

4.2 Analysis on Example Results

The overall planning model of the energy interconnection system is simulated and computed in the three scenarios shown in Table 1, and the construction of distribution lines and grids, the construction of energy conversion equipment and distributed power source capacity, the construction of different energy storage equipment and their average annual costs are shown in Table 5, Table 6, Table 7 and Table 8. As shown in the construction of power distribution network grids in Table 5, when the external power and gas supply capacity is abundant, the demand of the power distribution system for energy grid construction is minimal; when the energy supply is insufficient, the security and stability of the system network is reduced. The results in Table 6 show that power storage is the common choice in the three scenarios and operates in coordination with distributed power generation to help the system better achieve the supply-demand balance and effectively reduce the total cost of energy users. As shown in Table 7, the construction scales of HP and GG vary with the external power and gas supply capacity, mainly because they are the key energy supply elements of the electricity-centered energy Internet and the gas-centered energy Internet, respectively. In the case of short gas supply, GG construction will decrease, and P2G construction will increase correspondingly. As shown in Table 8, the total annual average cost is minimal in the three scenarios when the external power and gas supplies are sufficient. Fig. 10, Fig. 11 and Fig. 12 are diagrams of power, gas and heat systems in a typical day in winter in Scenario 1, respectively.

Table 5 New Power Distribution Lines in Three Scenarios

Power Distribution Line No.	Node *i*	Node *j*	Scenario 1	Scenario 2	Scenario 3
1	1	3	√	√	√
2	2	6		√	
3	3	13			
4	8	28	√	√	√
5	10	20	√	√	√
6	15	23			√

Table 6 Construction of Different Energy Storage Equipment (Unit: kW)

Energy Storage Type	Scenario 1	Scenario 2	Scenario 3
Power storage	30000	30000	30000
Gas storage	-	3000	-
Heat storage	-	-	-

Table 7 Construction of Energy Conversion Equipment and Distributed Power Sources (Unit: kW)

Energy Conversion Equipment	Scenario 1	Scenario 2	Scenario 3
GB	10000	10000	10000
GG	5000	2000	5000
CHP	-	-	-
CCHP	-	-	-
EH	10000	10000	10000
HP	20000	20000	10000
P2G	-	20000	-
PV power generation	20000	20000	30000
Wind power generation	20000	20000	20000

Table 8 Average Annual Costs in Three Scenarios (Unit: RMB 10,000)

Scenario Setting	Total Cost	Investment Cost	Operating Cost
Scenario 1	164040	35950	128090
Scenario 2	173780	34250	139530
Scenario 3	183910	45450	138460

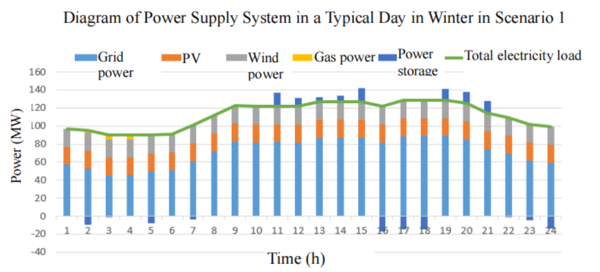

Figure 10. Diagram of Power Supply System in a Typical Day in Winter

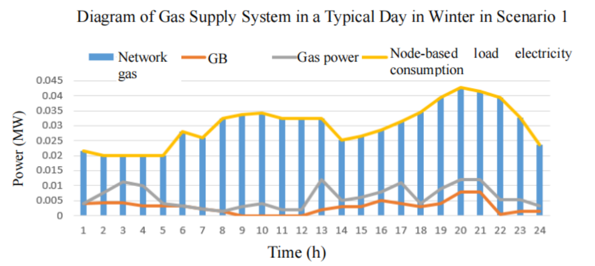

Figure 11. Diagram of Gas Supply System in a Typical Day in Winter

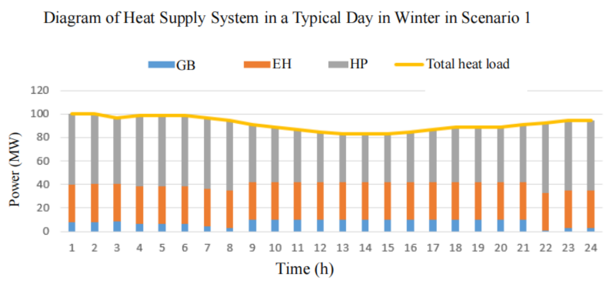

Figure 12. Diagram of Heat Supply System in a Typical Day in Winter

5. Conclusion

This paper first reviews the planning elements involved in the energy interconnection system under new-type urbanization and goes on to build a planning model system applicable to diverse energy use scenarios with the elements and scenarios as the core, with the comprehensive optimum of economic cost, environmental cost, energy efficiency and electrification rate as the aim, with the physical operational limitations of the energy interconnection system as the constraints, with diverse energy supply and consumption scenarios as the boundary conditions, and with the elements of the energy interconnection system as decision variables. It also provides a basic mathematical model, proposes the corresponding solution idea, and builds a comprehensive planning model that covers all the elements and different scenarios. Finally, the proposed method is tested in typical scenarios to prove that it can flexibly adapt to different energy supply and consumption scenarios and planning requirements and will provide general and practical value in the application of energy interconnection system planning under new-type urbanization and play an important role in supporting the high-quality and rapid advancement of new-type urbanization.

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