Urban Building Energy Planning With Space Distribution and Time Dynamic Simulation

Lin Fu

Zhonghai Zheng

Hongfa Di

Yi Jiang

Department of Building Science,
School of Architecture,
Tsinghua University,
Beijing 100084, PR China

It is important to deal with energy saving in buildings of one city level, and plan the energy system from one building to one city level. We strongly suggest conducting urban building energy planning (UBEP) in the urban planning field in China. There are two main characteristics of an urban building energy system. First, the terminal building energy demand is dynamically timely. Second, the energy demand, energy sources supply, energy equipments, and networks of heating, cooling, gas, and electricity, are distributed in an urban space. It is meaningful to conduct an innovative urban energy planning with space distribution and time dynamic simulation. Therefore, an UBEP simulation tool, developed by our research group, is introduced. Finally, a case of energy planning in Beijing City in 2010 for heating and air conditioning system is dynamically simulated and analyzed. To meet the same building energy demand in Beijing, such as heating, air conditioning, gas, and electricity, different energy equipments, such as boiler, combined heating and power, combined cooling, heating, and power system, and heat pump based on different energy sources, such as coal, gas, and electricity, should be planned alternatively. Also, an optimum urban energy system with high energy efficiency and low environmental emission can be achieved. This simulation tool contains most models of heating and cooling energy systems in China. We can validate the models with statistical data from previous or present simulation, and the simulation results in future planning can serve as guidance for the construction of municipal energy infrastructure. We can conclude that simulation in time dimension shows the characteristics of dynamic load in each nodes of the energy flow. The objective is to present the comparison of different scenarios and optimize the planning schemes. [DOI: 10.1115/1.3142725]

1 Introduction

With the rapid urbanization process in China at a level of 43.9% as of 2006 [1], researchers focused more on the increasing energy consumption in buildings and its environmental pollutant or CO_2 emission. Nationally, 63% of the annual energy consumption in buildings is consumed in cities and towns, that is, amounting to 16% of the whole nation's energy consumption in China as of 2004 [2]. The objective of this study is to develop a new method of urban energy planning to improve the whole performance of an urban energy system. What we refer to in this paper is the urban building energy planning (UBEP), which should be considered as the interdisciplinary science between energy planning and urban planning field. We can define the urban building energy system (UBES) as a system consisting of energy sources (such as coal, gas, oil, electricity, and renewable energy), energy transmission, distribution (such as electric power network, gas network, and heating network), energy conversion equipments (such as power plant, boiler, combined cooling, heating, and power system (CCHP), and heat pump), and terminal building consumers. As the lifeline of one city, this energy system inputs energy sources to terminal buildings and outputs pollutants and CO_2 emissions to the environment.

There are basically three types of energy special planning in China in urban master planning, urban regulatory detailed planning, or urban constructive detailed planning: heating planning, gas planning, and electric power planning [3]. As we all know, building energy demand can be divided into five types: heating, air conditioning, domestic hot water, gas for cooking, and electricity consumption, except air conditioning. Some general energy system of building heating and cooling demand in China can be simplified, as shown in Figs. 1 and 2. To meet the same energy demand in buildings, different energy equipments, such as boiler, heat pump, combined heating and power (CHP), and CCHP based on different energy sources such as coal, gas, oil, and electricity, can be planned. Similarly, building domestic hot water can be supplied by various energy equipments, such as household types of gas water heater, electricity water heater, solar water heater, or central types of heat pump, CCHP, and heating network. Different scales of energy systems from central, district, distributed, to dispersed type have their own advantage and disadvantage in energy efficiency, economic investment, operation cost, and environment emission, such as high energy efficiency and low environment emission in CHP system, but with a 10–15% heat loss in a heating network and relatively high investment. From this viewpoint, the heating, cooling, gas, and electricity demand should be integrated, due to the alternative energy sources and energy conversion equipments. In summary, it is suggested strongly to conduct an UBEP in urban planning in China from one building to one city level. Thus, the electricity and gas consumed by buildings, which affect greatly the energy structure in gas planning and electric power planning, can be analyzed further.

The theory of macroscopic energy planning, "three-energy" model, energy demand model, and energy economic analytical method, such as MARKAL, LEAP, MESSAGE, CGE, etc. [4–7], treat the energy system as a highly macro and abstract object. They are more suitable for analyzing energy policy and decision in a regional, national, or global scale. From the view of urban planning, the concrete energy system needs to extend fully in time and space dimensions based on an analysis of various energy systems and technologies, to guide the construction of municipal infrastructure. When referring to one concrete UBES, it should describe in

Contributed by the Solar Energy Engineering Division of ASME for publication in the JOURNAL OF SOLAR ENERGY ENGINEERING. Manuscript received August 28, 2008; final manuscript received November 8, 2008; published online July 14, 2009. Review conducted by Gregor P. Henze. Paper presented at the 2008 International Conference on Energy Sustainability (ES2008), Jacksonville, FL, August 10–14, 2008.

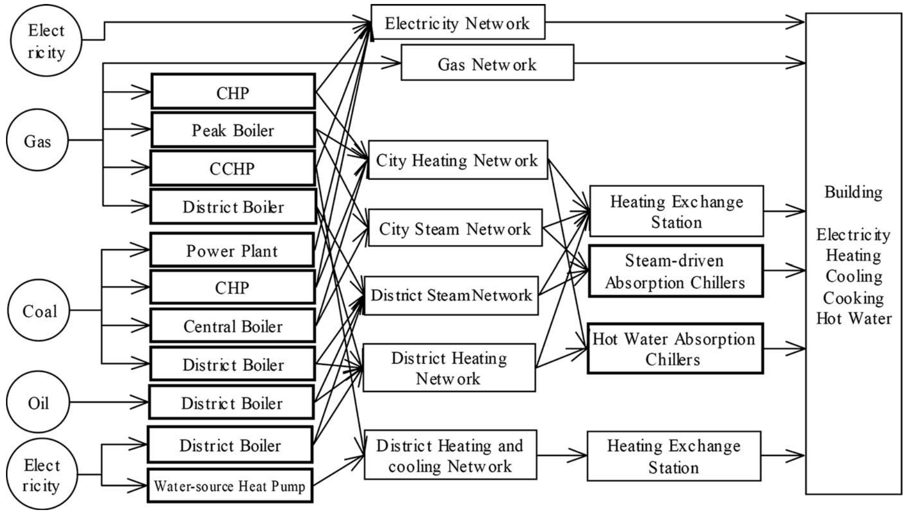

Fig. 1 Central and district building energy system

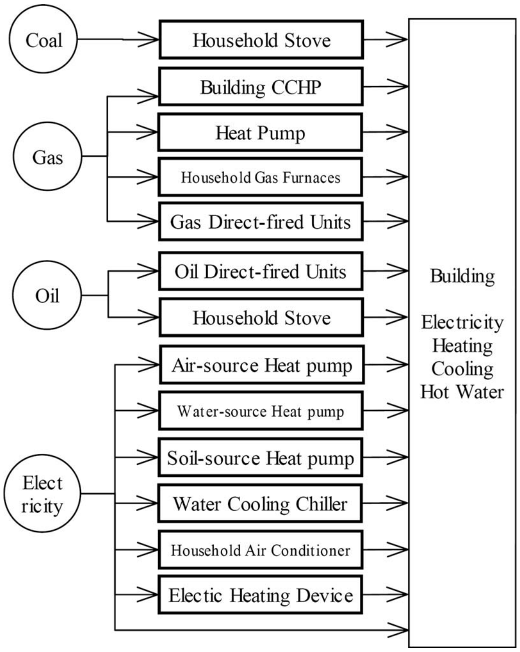

Fig. 2 Dispersed or distributed building energy system

detail the dynamic characteristics in time, and the geographical distribution in space, in order to expose the inherent rules and interaction among each energy subsystem. For instance, building heating and cooling load has the characteristics of dynamic seasonality, even hourly, with the variation in outdoor climate, as shown in Fig. 3. The dynamic load can be obtained either by analyzing actual energy consumption data or by building an energy simulation software such as DOE-2, ENERGYPLUS, and DEST. The location of the energy supply source and heating network in space is related closely with the urban geography, as shown in Fig. 4 [8]. The gas and electricity load share the similar characteristics. Space load density varies with various residential and commercial building types, architectural density, and floor area ratio. Therefore, the energy consumption is dynamic hourly with peak-valley load. For example, in Beijing City, more than 60% natural gas is consumed by heating and air conditioning, and most electricity load is consumed by air conditioning, which cause four times the gas and two times the electricity seasonal peak-valley load between winter and summer. From this point of view, the discharged environmental pollutants, CO_2 emission, and their ground concentration are dynamic in time and distribute in space.

Dynamic simulation can show in detail the characteristics of energy flow from supply to demand. The peak load of various load summation is needed for sizing the pipe network and equipment, and checking energy supply ability, infrastructure capacity, and environmental capacity. The average load is related to the objective of energy consumption, energy saving, and environment

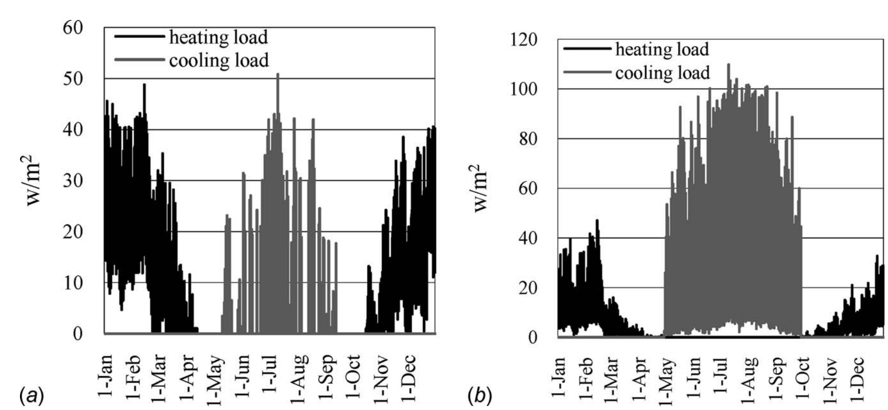

Fig. 3 Typical dynamic heating and cooling load of residential and commercial buildings in Beijing city (with the use of DEST software)

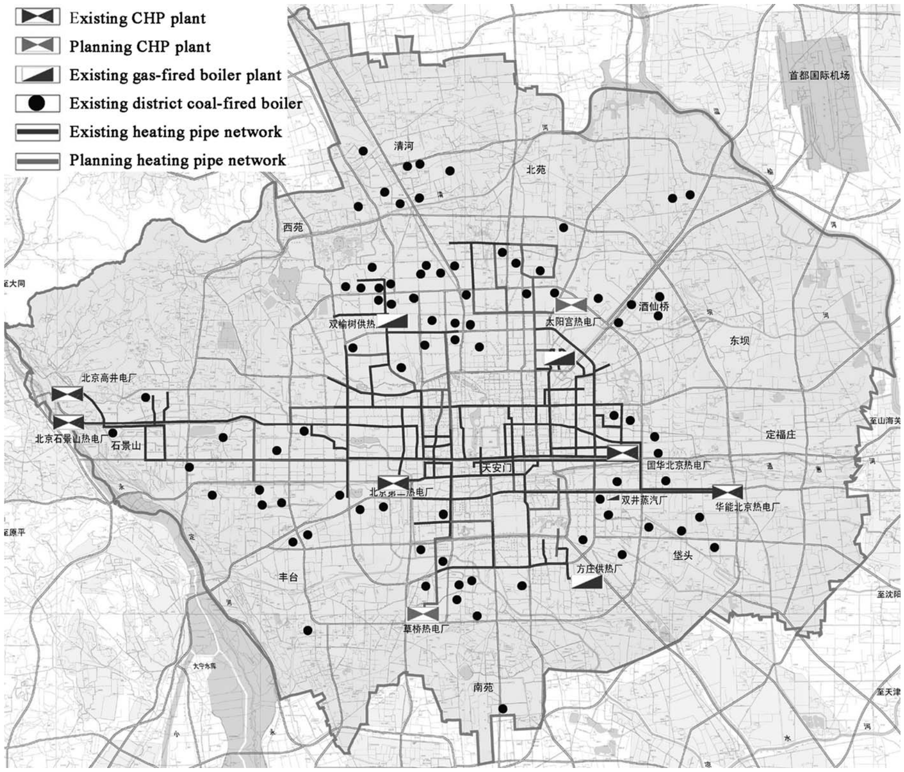

Fig. 4 Heating planning in Beijing city (2004–2020)

emission. Meanwhile, hourly data can analyze the hourly, daily, weekly, and seasonal characteristics of load to integrate the heating, cooling, gas, and electricity consumption in buildings. Finally, an optimal allocation and well alternative scheme can be developed. Thus, infrastructure capacity can be reduced and energy security can be assured.

2 New UBEP Method

Urban planning is not only a technical argumentation for an optimum scheme, but also a visual demonstration for city image in space. In this paper, we present a new UBEP method based on space distribution and time dynamic simulation. It mainly consists of three parts of contents: (1) the time dynamic characteristics and space distribution of building load indices, load demand, and energy system, thus, an urban energy database would be established; (2) the model of energy conversion equipment and energy system, including the energy efficiency, economic investment and cost, and environment emission; (3) the energy flow is simulated from energy source, network, to terminal building consumer; and (4) a comprehensive evaluation system for urban energy system to evaluate and optimize the planning scheme. In summary, we can follow the planning flow, as shown in Fig. 5.

As mentioned above, an UBEP simulation tool should be developed to simulate and gain the optimum planning scheme set by experts. Also, some other software such as the geographical information system (GIS) software (ESRI ARCGIS), environmental emission software (ISCST3), and heating and gas hydraulic calculation software would be used as the complementary tools to calculate and exhibit the visual result, such as the heating load density and the ground concentration of environment emission in space, shown in Figs. 6 and 7.

3 UBEP Simulation Tool

Although it is difficult to establish a comprehensive model to describe and optimize an urban energy system based on the model of each component of energy system and the energy flow from supply to the demand, developing a tool to simulate the planning schemes and to analyze the scenarios of the different systems is possible. Therefore, a simulation tool suitable for UBEP is developed, which includes most models of energy conversion equipments in heating and air conditioning in China.

We define energy conversion equipment as a certain kind of equipment or energy subsystem in one link of energy flow. The equipments would appear either in the central, district, distributed, building, or household system, such as network, heating exchange station, different type of boilers, water/air/soil source heat pump, gas turbine or engine cycle unit/gas-steam turbine combined cycle unit/back pressure, or extraction condensing steam turbine CHP system, CCHP system, gas direct-fired units, absorption chillers, screw chillers, centrifugal water chillers, and so on. The energy equipment models [9,10] could be considered as a black box with energy input and energy and emission output. For instance, the CHP system could be divided into four layers: coal, thermodynamic, electricity, and environment emission layer, with coal and electricity consumed, heating and electricity generated, and emission discharged in each layer, as shown in Fig. 8.

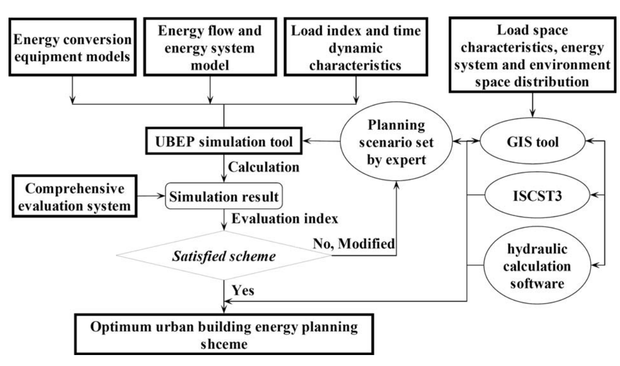

Fig. 5 Flow chart of an innovative UBEP method

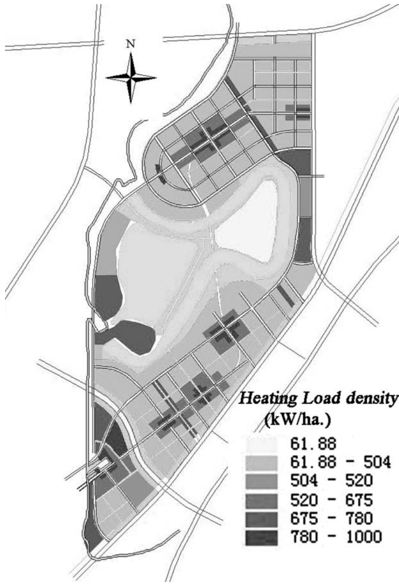

Fig. 6 The load density in space in heating planning of a certain district in China (with the use of ESRI ARCGIS)

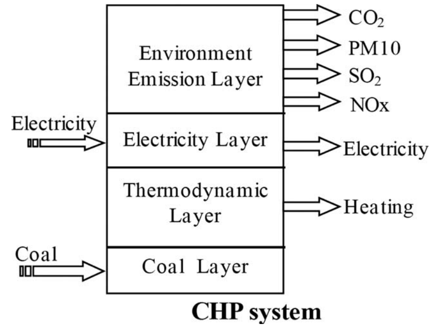

Fig. 8 The multilayer energy system model of CHP

The UBES can be expressed as a multilayer energy system model in "virtual" three dimensions with directed energy flow, shown as a simplified system in Fig. 9. There are totally eight layers in our simulation tool including coal, gas, electricity, oil, thermal (heating, cooling, steam, and domestic hot water system), environment emission (CO_2, SO_2, NO_x, PM10, etc.), strategy layer to allocate the energy flow, and the base layer containing the elements of all layers. The connecting lines show the relationships among the energy sources, energy conversion equipment, and the building user. As for the strategy layer, it needs some strategy to allocate the energy flow when there are multi-input relations from the upstream of energy flow to downstream. For example, the multiheat sources in a city's central heating network can be allocated in a prior sequence or equal sequence, as shown in Fig. 10. After a comprehensive investigation on the information of time dynamic and space distribution in energy system, energy supply, building energy demand, load indices, etc., the energy flow of this certain city can be established in the simulation tool. The model of this tool has been applied and validated in the Beijing Olympic energy planning [9–11]. This contains the models in heating and air conditioning, including 25 types of heating, 13 types of air conditioning, and 6 types of central domestic hot water. Different types of load indices are input hourly (8760 h), including heating and cooling domestic hot water load indices in both residential and commercial buildings in Beijing city.

4 Case Analysis

In this part, the building heating and air conditioning planning of Beijing city in 2010 is simulated and analyzed to demonstrate the application of this tool. In order to simulate the alternative energy system, it is supposed that the load indices, energy loss, and efficiency are the same in 2001 and 2010. Actually, the heating and cooling load indices, pipe network efficiency, energy efficiency, etc., should be made better after the various measure and management of building energy saving. The structure's central heating source is shown in Fig. 11. The consumer types in heating and air conditioning have a total building area of 426.5×10^6 m^2, and 61×10^6 m^2 domestic hot water users are centrally supplied, as shown in Table 1. The scenario is set under the consideration of reasonable development of high efficiency system, such as CCHP and water-source heat pump, substitution gas

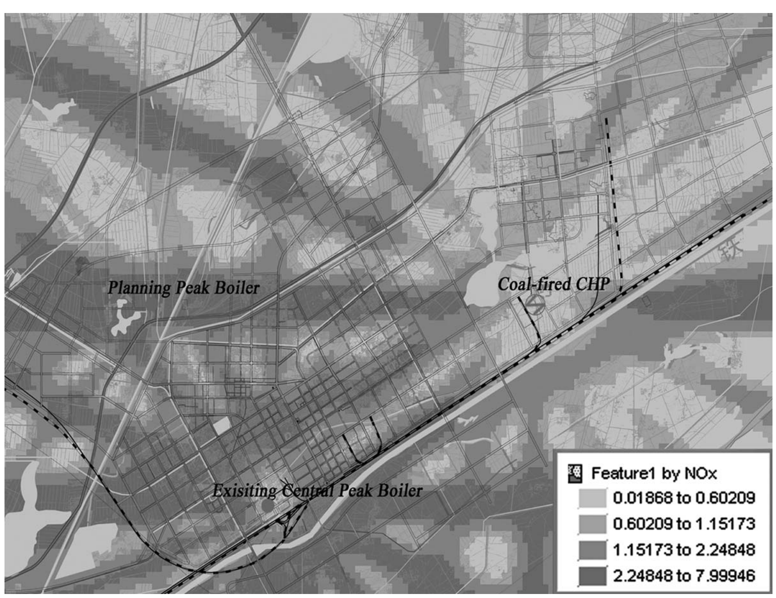

Fig. 7 The yearly average NO_x ground concentration ($\mu g/m^3$) in heating planning of a certain city in China (with the use of ISCST3 with GIS)

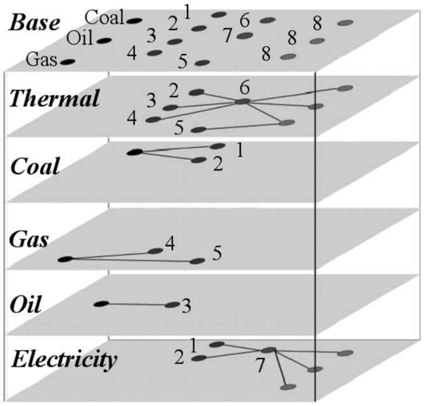

Fig. 9 Simplification of the multilayer energy system model and directed energy flow from energy source, energy conversion equipment, network to user or building. Where 1=Coal fired power plant, 2=Combined heating and power, 3=Oil-fired boiler, 4=Gas-fired boiler, 5=Household gas furnace, 6=Heating network, 7=Electricity network, 8=user or building

boiler for a small coal-fire boiler, step by step and full use of the ability of the city's central heating network, and so on.

Some simulation results are shown in Figs. 12–15. Through this tool, we can get the data of energy consumption and environment emission at each node of connecting lines of the energy flow. Here, the gas consumption refers only to the quantity consumed by energy conversion equipment in a heating and air conditioning system. The electricity consumption and power generation amount to the quantity consumed and generated only by energy conversion equipment and electricity demand in heating and air conditioning systems, such as the heating network circulatory power consumption. We can draw the conclusion that the input energy source (coal, gas, oil, and electricity) subtracted from the output energy source (power generated) is equal to 205 $kW\,h/m^2$ per year, which is about 1.65 times of the building load demand in heating and air conditioning systems in 2010. In other words, the efficiency of the whole urban energy systems is equal to 60%, while the value in 2001 is reached at about 2.1 times. Comparing the energy consumption and its environment emission with that of in 2001, we can achieve a reasonable energy planning system of high energy efficiency and low environment emission at the cost

Table 1 The building area of heating and cooling load demand (1×10^6 m^2)

	2001	2010
Heating user		
Central heating network	56.55	140
Central steam network	5	5
Coal-fired heating network	45.7	5
Gas-fired district steam network	1	10
Gas CCHP	0.05	22
Gas BCCHP	0.01	22
Gas-fired district heating network	15	52
Gas-fired boiler distributed	4	72
Household gas furnace	3	52
Gas direct-fired units	1	7.00
Water-source heat pump	1	15
Air-source heat pump	1	2.5
Electricity boiler heating network	2	2
Household electricity-fired stove	1	2
Electric heating	3	2
Oil-fired heating network	2.5	6.5
Oil-fired boiler distributed	0.4	6.5
Household oil-fired stove	1	1
Oil direct-fired units	0.02	1
Air conditioning users		
Central steam network	2.7	2.7
Central heating network	0.5	26
Gas CCHP	0.05	22
Gas BCCHP	0.01	22
Gas-fired district steam network	0.5	6
Gas direct-fired units	9.8	23.00
Oil direct-fired units	2.7	6
Water-source heat pump	1	15
Air-source heat pump	10	16.5
Chilled water units	10	35
Household air conditioner	120	160
Users without air conditioning	71.8	91.84
Hot water supply users		
Steam network of CHP in plant 1	1.2	1.2
Steam network of CHP in plant 2	1.9	1.9
Central heating network	10	26
Gas CCHP	0.05	13
Gas BCCHP	0.01	13
Water-source heat pump	1	6

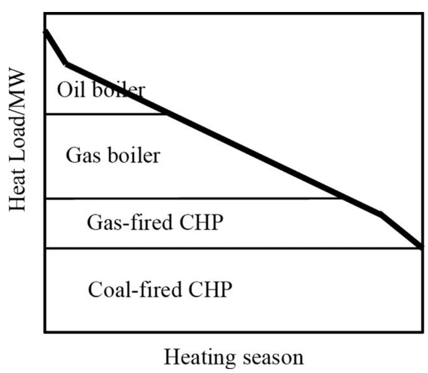

Fig. 10 The operation strategy of multiheat sources during heating season

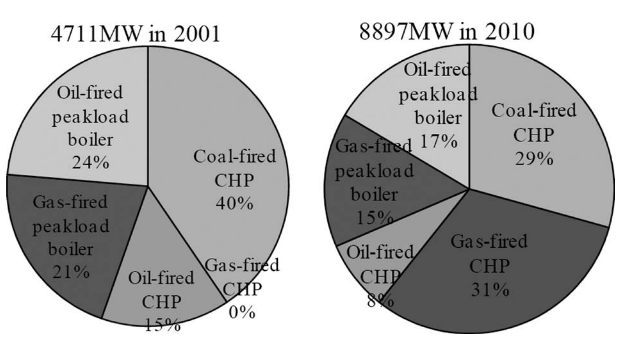

Fig. 11 The structure of city central heating source in 2001 and 2010

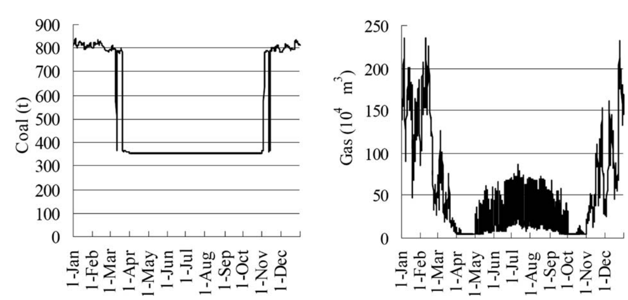

Fig. 12 The dynamic coal and gas consumption in 2010

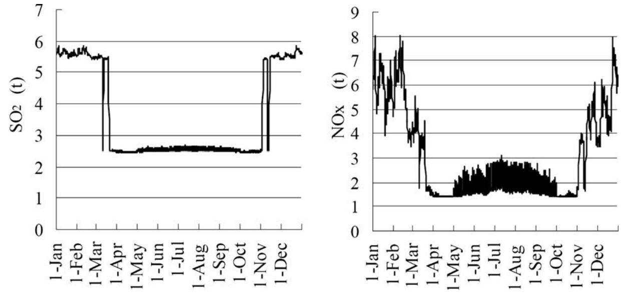

Fig. 13 The dynamic SO_2 and NO_x emission in 2010

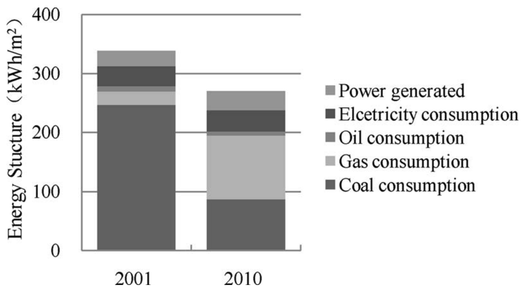

Fig. 14 The comparison of energy consumption between 2001 and 2010

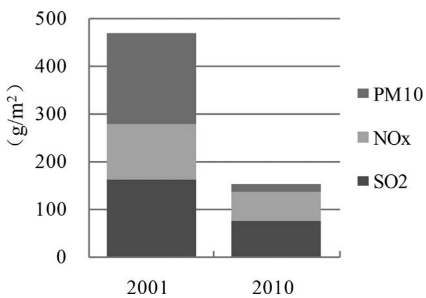

Fig. 15 The comparison of environment emission between 2001 and 2010

of gas consumption. From the viewpoint of dynamic simulation, the amount of gas consumption during winter is 4.2 times of that during summer.

More results of this energy system in 2010 can be analyzed in detail. For instance, more than 47% primary energy and 38% second energy (electricity power) would be consumed by the city's central heating system, and the power generated by the city's central CHP system and CCHP system share 56.7% and 43.3% individually. In the meantime, due to the majority of power output in the city's central heating system, more than 97% SO_2 and 63% NO_x would be emitted by the city's central heating system, especially because of coal consumption, which can be seen from the similarity dynamic curve between Figs. 12 and 13. To meet the same energy demand in buildings, we can set up different scenarios of development. Thus, the different alternative schemes can be simulated and evaluated. Furthermore, with the technical progress of energy saving, more scenarios can be analyzed when the load indices, energy loss, and energy efficiency would be improved in the planning period.

5 Conclusions

We can draw some conclusions and present some prospects as follows. (1) Although the energy source structure and performance of the energy system are different between China and other countries, the planning method, and this simulation tool, can be also applied to the energy system in other cities. (2) Most models of heating and cooling energy systems in China are validated and contained in the simulation tool. (3) We strongly suggest the conducting of an innovative UBEP with space distribution and time dynamic simulation in urban planning systems in China. Simulation in time dimension shows the characteristics of dynamic peak-valley load in each node of energy flow. So the urban infrastructure capacity energy supply ability and environmental capacity can be determined and validated. Also, the diverse characteristics of load in heating, cooling, gas, and electricity can be integrated. The objective is to present the comparison of different scenarios to optimize the planning schemes. (4) In a case study, we can validate the models with statistical data in previous or present simulation, and the simulation results in future planning can serve as guidance to the construction of municipal energy infrastructure. (5) In future research, we should add economic investment and cost into the models of energy conversion equipment. More models of other new energy systems, such as renewable energy systems, should be established. Furthermore, a comprehensive evaluation system for an urban energy system should be developed. We should analyze the characteristics and new theory of space distribution by means of a geographical information system tool. In summary, in concern with building energy-saving, municipal infrastructure investment, and environmental problem, it is crucial to have an integrated urban energy planning from a microscopic building level to macroscopic and technical city level.

Acknowledgment

This research is financially supported by National Key Technologies R&D Program for the 11th Five-Year Plan (Contract No. 2006BAJ03B01). The authors also particularly wish to thank the urban energy planning research team in Energy Research Building Center of Tsinghua University, on the aspects that this paper is based on.

References

[1] 2007, *China Statistic Yearbook*, National Bureau of Statistics of China, Beijing.
[2] 2008, *2008 Annual Report on China Building Energy Efficiency*, Energy Research Building Center of Tsinghua University, Beijing.
[3] Dai, S., 1999, *Urban Engineering System Planning*, China Building Industry, Beijing.
[4] Qiu, D., 1995, *Energy Planning and System Analysis*, Tsinghua University, Beijing.
[5] Jifeng, L., and Aling, Z., 2006, "Review on the Development of Integrated Energy-Economy-Environment Assessment Model in the World," Energy Policy, **5**, pp. 33–39.
[6] Capros, P., 1995, "Integrated Economy-Energy-Environment Models," International Symposium on Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making, IAEA, Vienna, Austria.
[7] Hiremath, R. B., Shikha, S., and Ravindranath, N. H., 2007, "Decentralized Energy Planning: Modeling and Application: A Review," Renewable Sustainable Energy Rev., **11**(5), pp. 729–752.
[8] Beijing Municipal Government, 2004, "Urban Master Planning in Beijing," Report No. 2004-2020.
[9] Sui, J., 2003, "Dynamic Analysis Method of the Urban Energy System," Tsinghua University, Beijing, Postdoctoral Report.
[10] Li, N., 2003, "Study on the Application of Geographical Information System (GIS) in HVAC System," MS thesis, Tsinghua University, Beijing.
[11] Chen, J., 2007, "City Energy System Dynamic Model Based on Energy Equipment Characteristics," MS thesis, Tsinghua University, Beijing.