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Forecasting Residential Energy Demand in China: An approach to technology impacts

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Abstract

China is undergoing rapid economic development, and experiencing increased energy consumption. An accurate prediction of residential energy demand is beneficial to both energy supply decision-making at the local level and energy policy makers at the national level. It provides the most likely trend of residential energy demand in the specified areas and how the trend may be controlled by technologies and policies. Complexity and difficulty exist regarding the forecasting of energy demand because there are too many variables and uncertainties that may have significant impact, and also because essential historical data regarding residential energy consumption is in most cases inadequate. Unlike most existing models, we have developed a multiple-level forecasting model, with a focus on the impacts of technologies. Essentially, there are four levels in this forecasting system: the household model, community model, city model, and national model. Each level of the model has its own focused variables so that other variables can be isolated to reduce the complexity and difficulty of model implementation. This paper outlines the framework of this forecasting model and details the two lowest levels: household and community level models.

Keywords: residential buildings, energy-demand forecasting, households model, building energy simulation

Introduction

China is the most populated country and the second largest energy consumer after the USA. Recent economic growth has exceeded the growth of population, resulting in improvement of the overall living standard of people [1]. China has relatively limited energy resources, which are unevenly distributed, mostly in remote areas whilst the majority of energy end-users are in the eastern coastal areas. Insufficient energy transportation results in bottlenecks in the supply of energy to end-users. China also suffers from low efficiency of energy conversion and consumption. Coupled with this is the fact that coal, which accounts for 75% of total energy supply, has a heavy impact on the environment. Therefore, government energy policy is to improve its overall energy efficiency throughout the entire energy system, from production, conversion, to end-use consumption.

The residential sector represents an increasing share over the overall energy demand, developing an enormous stress on the energy system. Therefore, a number of residential energy conservation regulations have been established, but how these approaches actually influence residential energy consumption has not been systematically evaluated. The result is that optimum technological combination is absent in these energy conservation regulations. Because the available essential data regarding residential energy consumption in the past is inadequate, no existing residential forecasting models, which are based on the conditions in developed countries, can be directly applied. Therefore, a forecasting model is needed for analysing the trend of residential energy and how the trend can be varied by technological and economic variables at the local and national levels.

This study aims to establish an initial approach to this forecasting system, and to that end proposes a four-level model approach. Historical residential energy data are essential in supporting the implementation of each level of the model, and is also essential in developing methodology to obtain and retrieve the needed data. Because of the limitation of resources, this study will only focus on the technological impact at the household and community level. This however does not necessarily indicate that the others are of less importance. The study forms the primary framework of the system and defines the necessary interfaces between different levels of the models.

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Chinese economy and energy

China has been suffering serious energy and environmental problems while experiencing rapid economic growth. In the interest of understanding the overall situation, the following basic literature studies have been conducted:

a. The energy system in China: the past, current, and estimated future.
b. The energy reserves and resources in China.
c. Energy conversion and production.
d. Energy consumption.
e. Environmental impacts caused by energy production, conversion, and consumption.
f. National level of energy prediction.

Figure 1 presents the GDP in China from 1979 to 1997 (NSDC 1998, DCE 1998, McCreary and Gu 1996). From 1992 to 1997, with a GDP growth rate of over 9.5%, China has the world's fastest growing economy. Despite the recent Asian economic crisis and the historic flood in 1998, China still maintained an 8% economic growth rate during the past two years. China's huge population has put numerous stresses on the development of the nation, but on the other hand, it also offers an abundant labour resource and a potential market, creating room for consistent economic growth. From the fourth quarter of 1998 to the end of 1999, although China has suffered severely from the negative consequence of the Asian financial crisis, a mass of purposely-increased domestic investments have successfully avoided the collapse of the national economy. With a gradual 'Wake-up' of the economy in those Asian countries that have been deeply involved in and suffered from the 1997 crisis, China begins to record noticeable growth in export. Although the reform of the big state-owned companies is still far behind the expected pace and success, China will maintain a consistently high economic growth rate and its entry into the WTO at the end of 1999 will force it to open its doors much wider to the outside world. Many reputable economists have predicted a high level of long term economic growth in China, and the World Bank forecasts that China will double its GDP based on 1997 in ten years time.

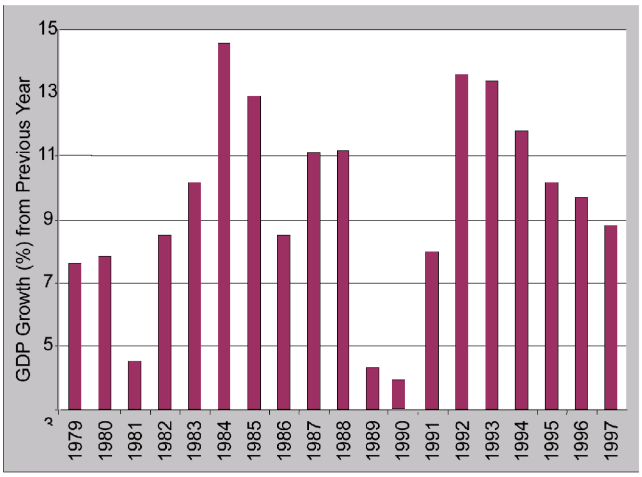

Fig. 1. China's annual GDP Growth (%)(NSDC 1998, DCE 1998, McCreary and Gu 1996)

This rapid pace of economic growth and spread of industrialisation throughout the country has caused economic strain, which is particularly noticeable in the inability of Chinese commercial fuel production to keep pace with demand. From 1985 to 1995, a period in which China's GDP has increased by 150% - calculated from Chinese Yuan as shown in Figure 2 after adjustment for inflation, its primary energy production capacity has only been increased by 80%. The considerable discrepancy exists between energy supply and demand (McCreary and Gu 1996). The high dependence of economic development on its ability of domestic energy production can be clearly seen. This obviously has an adverse impact on economic development, and energy consumption in China has been restricted by its electricity generation capacity. Over an overwhelming period since 1949, the overall national primary energy balance has been maintained between its net production and consumption, while energy import and export have contributed insignificantly until the 1990's.

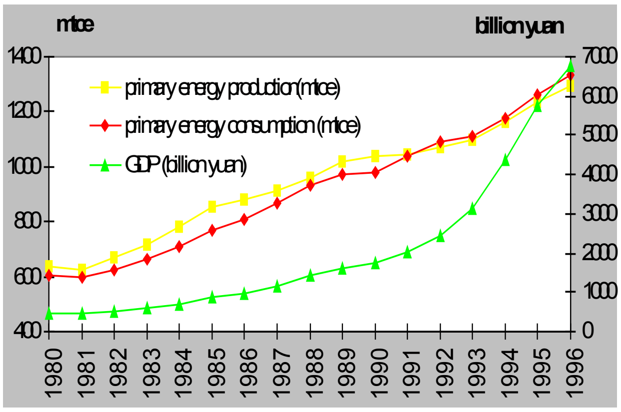

Fig. 2. China's Energy and GDP 1996-98(NSDC 1998, DCE 1998, McCreary and Gu 1996)

With consistent economic growth predicted for the long-term, the limited energy reserves and production in China will affect the international energy supply. On the other hand, China has to develop its energy production, including utilisation of renewable energy. Also, China still has enormous room to save energy if energy efficient technologies can be widely applied. In this context, the building sector's overall energy efficiency is very low because most existing buildings were built without sufficiently utilising energy efficient technologies [Tu and Paul 1996, Xu et. al. 1996]. The potential for energy saving in the building sector therefore presents both remarkable opportunities and challenges.

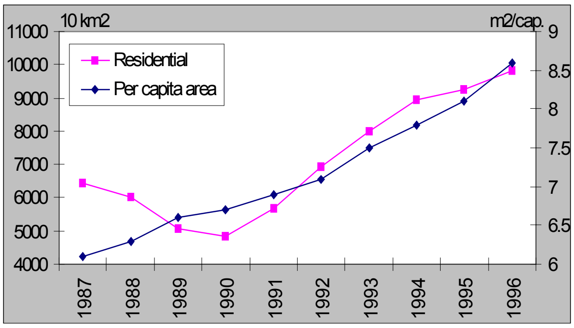

Fig. 3. Annually completed dwellings and average liveable residential floor area per capita in China

Residential Development And Energy Issues

Residential stock has been mushrooming during the last two decades because about 50 to 100 million square meters of new residential buildings are built annually. Figure 3 presents a profile of annually completed residential building and the growth of per capita liveable residential area from 1987 to 1996. It indicates that China has kept a consistently high volume of net annual residential construction. A slight drop is shown from 1988 to 1991, which is related to the reduced growth of GDP as seen in Figure 1. However, per capita residential liveable space has seen a consistent growth. In fact, in more recent years, the annually completed residential floor space has reached around 800 million m^2.

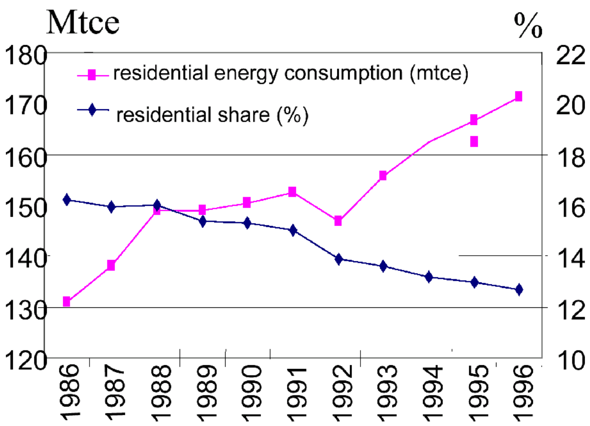

Fig. 4. Primary Energy Consumption by Residential Sector

To match the massive demand for residential buildings, the Chinese government has developed three different residential plans. Each plan focuses on development of a certain level of residential buildings. The "Juzhe You Qiwu"(Inhabitants have their dwellings) Project develops residential buildings of a basic level that is affordable for most residents. The "Anju" (Satisfactory Dwellings) Residential Project develops residential buildings for mid-level income families. The "2000 Xiao Kang" (comfortable dwelling) Residential Project develops high level residential buildings. It is required that all these development must comply with the latest version of residential energy conservation regulations. Although the building level might be different from location to location, it is possible to specify the three types differently in term of energy performance. Besides the government-organised development, private developers play an increasingly important role in the residential industry. Normally there is no limitation on building standard for this kind of development, but it is strictedly required that energy conservation regulations be satisfied.

On the other hand, residential energy intensity (the energy demand per household) has been increased because of consistently improved living standard (Jonathan et al 1992). It should be noted that, due to historical and technical reasons, most existing residential buildings were built with low energy efficient technologies. The merging effects of these two factors caused a large increase in energy demand in the residential sector. Figure 4 presents the energy consumption of residential sector from 1986 to 1996. Although the share of residential energy has been consistently decreasing during this period, the amount has increased by 35%. A rapid growth is found since 1994. Recent data indicates that the consumption in 1999 probably exceeds 200 Mtce. It is predicted that residential energy demand will maintain consistently high growth for a long-time. Huge energy saving could therefore be created and realised if energy efficient technologies are applied to retrofit old buildings.

Social Survey

To accurately predict residential energy use, it is essential to understand the social-economic factors that affect it. These factors may decide the intensity of energy use in the following ways: a). indoor climate control (essentially in cooling and heating, humidification and dehumidification, and lighting); b). Domestic convenience appliances (clothing washing and drying, etc); c). Food processing, cooking and food storage; d). Home recreational appliances, TV, computer, etc. We used social survey method, with the aim of ascertaining the relationship between the use of these technologies and the family income in relation to the social norm. Part of the analysis is presented here.

A number of social surveys were conducted to obtain the essential data regarding historical residential energy consumption and the relevant parameters in two significantly different climatic and economic conditions. They are Beijing and Yichang (in Hubei Province). Fuel gas, electricity, and hot water information have been collected via social surveys. Figure 5a, 5b, and 6 present some of the survey results of the two cities.

In Yichang, Hubei,

(1) On average, annual electricity consumption has been doubled from 460 kWh in 1992 to 921 kWh in 1997, although the average level is still lower than Beijing.

(2) More than 50% of the families surveyed have doubled their electricity consumption over a period of less than five years. The annual growth rate in Yichang is higher than Beijing. This is because Yichang had greater potential for residential energy demand when the economy began to improve.

(3) Annual growth rate of electricity consumption from 1992 to 1997 has remained steady at a high level. The profile of electricity consumption for this period indicates that rapid growth of electricity consumption in Yichang, Hubei will remain for at least five years.

(4) It is found that 25% of the units often run their air-conditioners in the summer. The percentage is a little lower than Beijing, but it is growing faster. It can be explained because Yichang is located in *the Central China Hot Summer/Cold Winter Climatic Zone.*

(5) Relatively higher electricity consumption is also found in the winter. This is because Yichang needs heating during this season but there is no heating distribution system in this city. So portable electricity heaters are used as a replacement. This represents large potential electricity consumption. It can be expected that more electricity will be consumed for heating during the cold season in the future. Similar phenomena should be found in cities with similar climatic conditions.

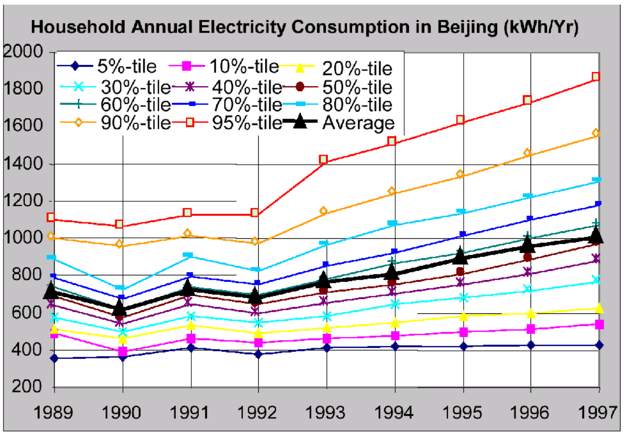

Fig. 5a. Annual Residential Electricity Consumption in Beijing

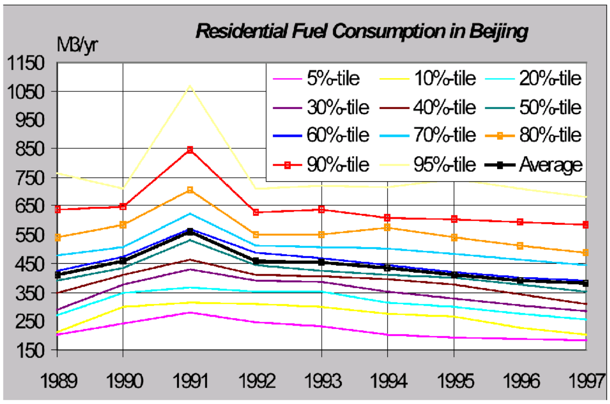

Fig. 5b. Annual Residential Fuel Consumption in Beijing

In Beijing,

(1) The annual household electricity consumption has increased by 85% from 600 kWh in 1990 to 1000 kWh in 1997.

(2) 40% of the surveyed families have doubled their annual electricity consumption during the period while the other 30% have increased their electricity consumption by only 20%. (3) In 1997, 30% of the families surveyed annually consumed 1200 kWh of electricity, and there are significant seasonal differences. Most of these families have maximum electricity consumption during the third quarter at a level doubling the annual average. This means that they often operate air-conditioners. A nation wide survey about ownership of domestic air-conditioners shows that 32.7% of residential units are equipped with air-conditioners. The difference between the two numbers can be explained because the air-conditioners might not often be operated in some units.

(4) On average, annual electricity use per unit has been steadily increasing at an annual growth of 5% to 8%. The profile of electricity consumption for this period (1990-1997) very clearly indicates that the growth trend will remain for quite a long time.

(5) In contrast, fuel gas consumption has been slightly decreased by 8% from 1990 to 1997. Almost 100% of units have reduced their consumption of fuel gas. This phenomenon can be explained because families are changing their traditional life style as their incomes increase – people do less cooking at home.

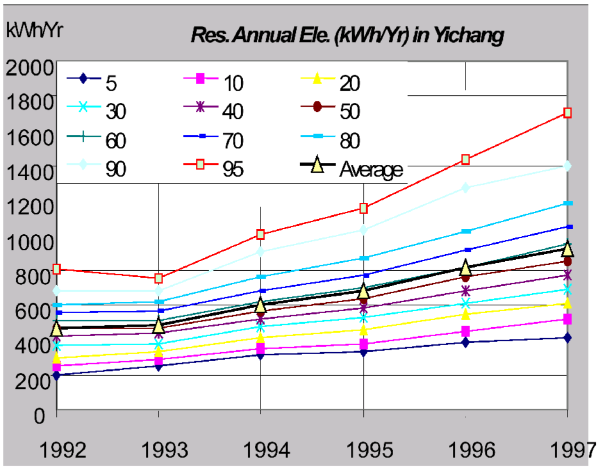

Fig. 6. Annual Residential Electricity Consumption in Yichang

In both cities, seasonal differences in electricity consumption have been increasing steadily from 1992 to 1997. The maximum consumption occurs in the third quarter when it is necessary to run air-conditioners or fans. More electricity is consumed for domestic appliances as they become more affordable. As family income increases, most families are changing their traditional life style, resulting in decreased fuel gas consumption. It is not found that energy efficient technology has a significant impact on residential energy saving. Especially in Beijing, no adequate evidence indicates that buildings' envelop improvement projects have significantly altered energy efficiency of residential buildings.

The social survey study leads to an understanding on how residential energy consumption has been changing during the last seven years. The result also indicates a possible trend in the future.

Energy Efficient Technologies

The focus of this project is to analyse the impact of energy efficient technologies (EET) on residential energy demand [Boedecker, et al. 1996, DOE 1996]. It is essential to understand what EETs are available and what EETs are locally applicable in a concerned location. EETs for residential buildings are categorised in this project by the following five groups:

a. Indoor climate control technologies.
b. Building envelope.
c. Other domestic appliances.
d. Lighting.
e. Control.

Here, we only discuss the indoor climate control technologies and building envelope. Devices for space conditioning include home air-conditioners, electric heaters, dehumidifiers, humidifiers, electric fans, ionisers, and the radiators of central heating systems. This part largely constitutes the total energy demand. Application of EETs can produce significant energy savings. There are several types of home air-conditioners, including the unitary window type, split type, multiple-cooler type, variable frequency type, removable type, and heat-pump type. Steady-state efficiency rating (EER) can be used to quantify the energy efficiency of room air-conditioners. The EER of air-conditioners marketed in China might vary from 6 to 12. Therefore the market share of different air-conditioners and ownership of air-conditioners determines the distribution of per household energy in residential communities. So it is also essential to collect the relevant data. Figure 7 shows the ownership of air-conditioners in Beijing from 1992 to 1998.

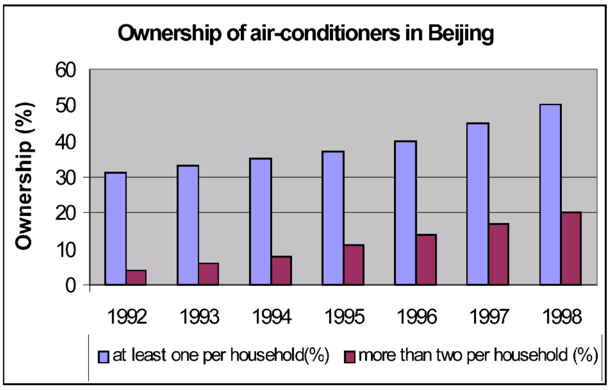

Fig. 7. Ownership of air-conditioners in Beijing

The thermal performance of a building envelope is determined integrally by a number of relevant variables. The major variables concerned include:

a. The construction of external walls.
b. The construction of windows and doors.
c. The construction of roofs and floors.

According to a social survey, six typical types of residential flats have been specified, including:

a. Studio: single room measuring 15 m^2.
b. One-bedroom flat (OBF): one bedroom with one living room, kitchen, and bathroom, measuring 15-30 m^2.
c. Two-bedroom flat (TBF): two bedrooms with one living room, kitchen, and bathroom, measuring 30-65 m^2.
d. Three-bedroom flat (SBF): three bedrooms with one living room, kitchen and bathroom, measuring 65-90 m^2.
e. Three-bedroom plus flat (TBPF): three bedrooms with one living room, one reception, one kitchen and two bathrooms, measuring 90-150 m^2.
f. Top flat (TF): any flat bigger than type-e

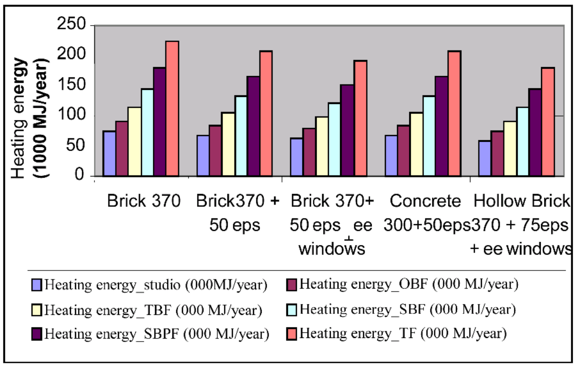

Fig. 8. Heating energy regarding different constructions in Beijing

Thermal simulation has been performed to analyse the impacts of different EET on the energy consumption of each type of residential flat (Liao 2001). Figure 8 presents a sample of results that shows the impact of different insulation on energy consumption of different types of flat in Beijing. A number of such analyses have been conducted in order to produce essential data for the household model. A climatic data base and residential material database have been developed for this project.

Four-Level Residential Energy Forecasting Model

A prediction of residential energy demand at the national level relies on a mass of statistical data, including availability and price of energy, climatic condition, economic indices, and energy end-use devices. In fact these data form the relevant variables that determine the trend of residential energy demand at the specified region. The relationship between the national residential energy demand and these relevant variables is complicated. Besides, a correlation also exists among these relevant variables. Therefore it is difficult, if not impossible, to develop a macro level of model that addresses all these relevant issues without the essential supporting data. Unfortunately, the availability of such data is extremely insufficient throughout China. In this study, attention has been concentrated on the development of a forecasting model that presents the impact of energy efficient technologies. To simplify the problem, namely to eliminate the complexity and difficulty caused by economic, climatic, and political issues, a multiple-level forecasting model has been developed so that, on one of the levels, technologies can be isolated from others and analysed separately. The national residential energy demand (E_N) is a function of the following relevant variables:

(1) Availability of energy supply;
(2) The price of energy deliverable to residential buildings;
(3) Climatic conditions;
(4) Economic indices;
(5) The behaviour of residents;
(6) Residential energy end-using devices and the technologies applied.

If historical data existed, there would have been a chance to derive a correlation between E_N and these variables although this still is difficult. This correlation could then be employed to make a prediction for given scenarios of relevant variables. To analyse the impacts of energy efficient technologies, it would simplify the problem if other issues are treated as constant rather than variables.

The energy end-user in the residential sector are individual households. A group of households form a residential community, a city consists of a number of different residential communities, and a country consists of a number of cities. Therefore, in the study, the forecasting model is developed at four corresponding levels:

(1) Household model: The outputs are household energy intensity (HEI in kW), household energy constraints (HEC in kW), and household energy consumption (HEU in kWh). A household model consists of four parts: energy delivered, energy consuming devices, people, and energy consumption.
(2) Community model: The outputs are community energy intensity (CEI in kW), community energy constraints (CEC in kW), and community energy consumption (CEU in kWh). In a community model, all households are classified into a number of clusters in terms of energy intensity and energy consumption respectively. So the distribution of these clusters determines the outputs of a community model.
(3) City model: The outputs are city energy intensity (LEI in kW), city energy constraints (LEC in kW), and city energy consumption (LEU in kWh). Similarly, all communities are classified into a number of clusters in terms of energy intensity and consumption respectively. The communities falling in same cluster are said to have identical energy intensity or consumption. The distribution of these clusters then determines the outputs of a city model.
(4) Country model: the outputs are national energy intensity (NEI in kW), national energy capacity (NEC in kW), and national energy consumption (NEU in kWh).

Figure 9 presents the schematics of this four-level forecasting model. Our study is aimed at developing the overall framework of the four levels of model and details the first two, i.e., the household model and community model. Analysis on the impact of individual energy efficient technologies can be established in household level, and the applicability of these technologies can be studied in the community model.

Figure 10 presents the basic components of a household model. Energy delivered to households includes:

(1) Electricity
(2) Fuel gas
(3) Hot water
(4) Miscellaneous.

The amount of energy source available to a household determines the energy constraint. On the other hand, the activities involved in energy consumption within a residential household can be categorised into three groups: thermal environment control (mainly heating/cooling), lighting, and miscellaneous (covering all other energy consumption). Therefore total energy consumption E_H can be broken down into three components:

$$E_H = E_H^T + E_H^L + E_H^M$$

where:

E_H^T : Energy consumed to control the thermal environment in a residential household.

E_H^L : Lighting energy in a residential household.

E_H^M : Energy consumed for all other activities in a residential household.

Each term on the right side of the equation can be modelled separately by three sub-models in our Residential Household energy model (RHEM), which physically models the energy processes involved within residential households. Because these processes, including the control of thermal environment (thermal), lighting, and miscellaneous, are of significantly different physical characteristics, RHEM contains three components that each models one process. T-model simulates the thermal dynamics of residential households and the services devices and systems. It can predict the thermal performance and energy consumed for thermal control of a residential household. The technologies of the current practice (Liao 2001)) can be quantitatively represented in the T-model and therefore their impacts can be studied. The L-model represents the principle of lighting within a household. The efficacy of luminaires, architectural design of indoor space, and lighting control, are represented in the model. For example, to illuminate a room to 350 Lux, a 50 watt lamp may be needed if it is an incandescent one. If a compact fluorescent lamp is used, the electrical power may be reduced to below 15 watt. The relevant technologies may change these elements and consequently affect the lighting energy consumption. The M-model represents all other energy processes (M-process). This study focuses on thermal control and lighting, and the M-processes do not involve any complicated physics, therefore the M-model just simply represents the average long-term annual characteristics of the processes.

To illustrate the T-model, Figure 11 presents statistics of the energy consumption of a household in Beijing. It shows that when the averaged outdoor temperature is less than a certain value, T_{ref_h} in this figure, the daily equivalent electricity consumption proportionally decreases when the temperature rises. When the averaged outdoor temperature is higher than a certain level, another T_{ref_c} in this figure, the daily equivalent electricity rises when the temperature rises. During the transition season when the daily averaged temperature falls between T_{ref_h} and T_{ref_c}, the daily equivalent electricity consumption does not change with the external conditions.

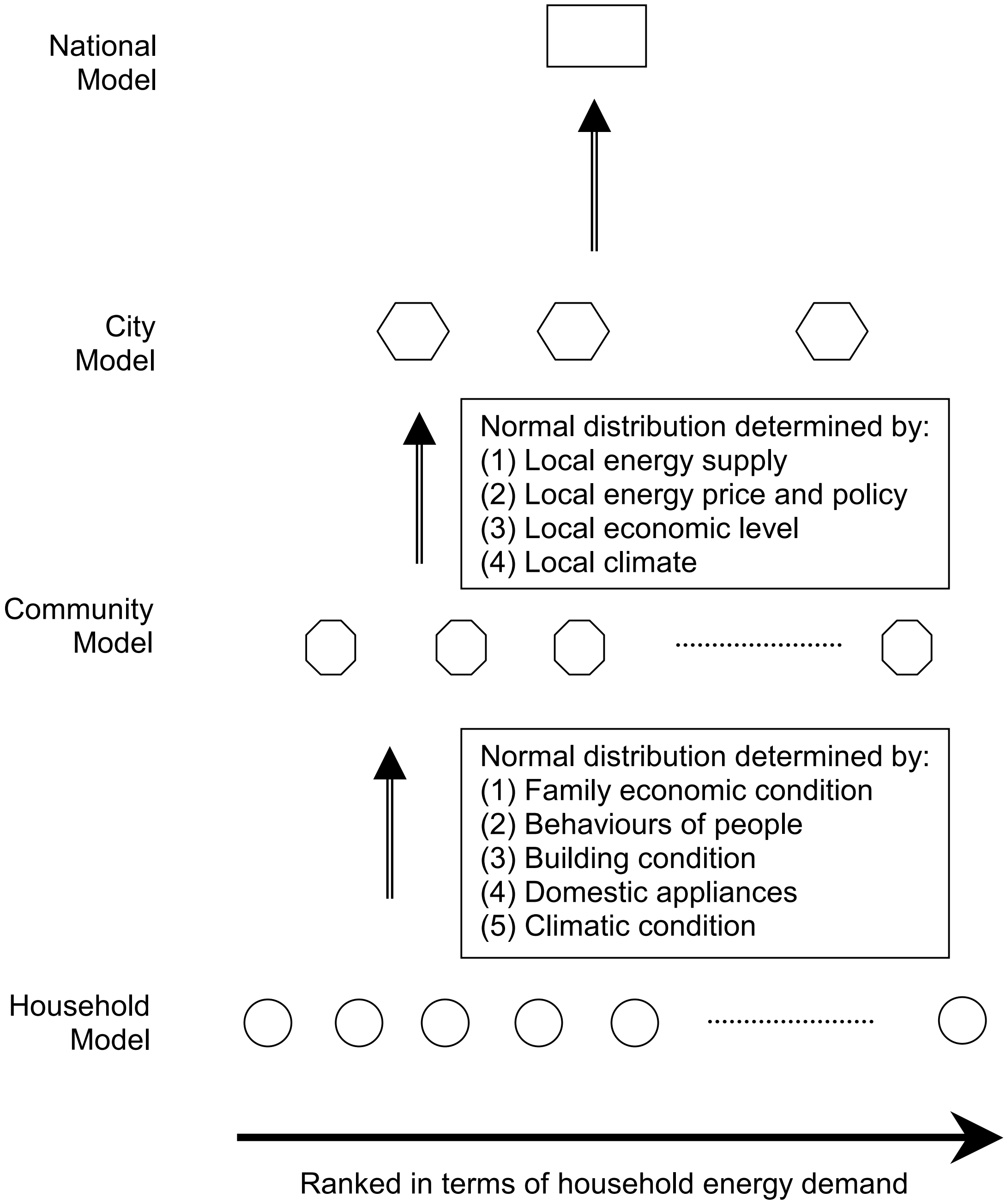

Fig. 9. The structure of four-level of residential energy forecasting model

In Figure 11, the slope of the heating season depends on the following factors:

(1) The thermal performance of the building envelope.

(2) The control performance of the heating terminals.

(3). The behaviour of the tenants.

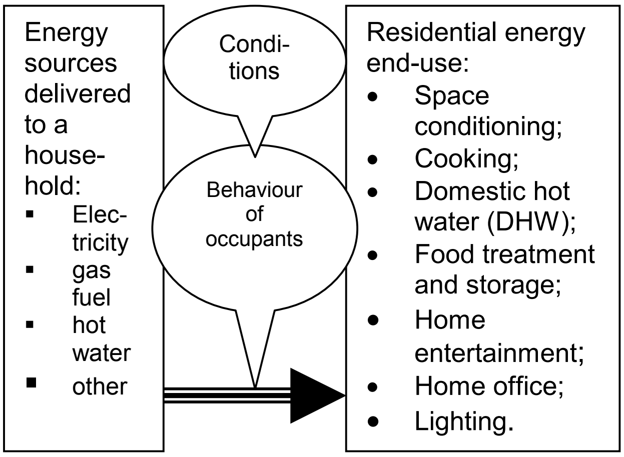

Fig. 10. Energy system at the household level

Similarly, the slope of the cooling season depends on the following factors:

(1) The thermal performance of the building envelop.

(2) The performance of the air-conditioning devices, including electric fans, air-conditioners, and dehumidifiers.

(3) The control performance of the devices.

(4) And the behaviour of the tenants.

During the transient period, when no heating or cooling is required, energy is consumed for climatic-independent tasks, such as lighting, cooking, and home entertainment. But technology also has significant impact on this energy.

The behaviour of tenants plays a decisive role in determining the actual energy consumption as it varies the use pattern of these devices (Haas et al 1998, Papakostas and Sotiropoulos 1997), but this is very complicated because there are so many relevant factors that are fuzzy and uncertain. The relationship between them will be investigated based on our social survey study. Space conditioning accounts for a big percentage of the total annual energy consumption. Tenants has significant impact on this by varying the set-point of temperature and schedule, although in many occasions the pertinent devices do not offer facilities for such changes. Technological progress making this operation possible will create a big potential for household energy reduction.

A household model basically represents how the energy demand and consumption can be influenced. That means that a number of correlations between each individual relevant factor and energy have to be quantified. To obtain these relations, thermal simulation technique is used to analyse the impact of the space conditioning related technologies. The inputs to these analysis tools include:

(1) Climatic conditions. Two different types of climatic data have been used: TMY and statistic-historical-data-based generation.

(2) The thermal performance of residential building components.

(3) Historical residential energy consumption and relevant data. The study has been conducted with a focus on only three selected locations that have significant different climatic and economic conditions. However, the methodology developed is suitable for other locations throughout China. This social survey is to relate household income to the use patterns of electrical appliances.

(4) Tariffs of residential energy in different locations.

(5) Energy related data of common domestic appliances.

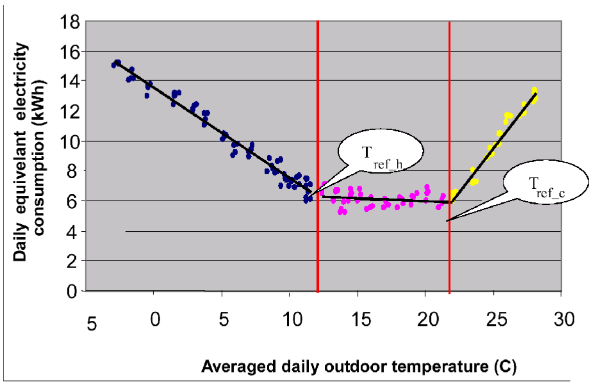

Fig. 11. The equivalent electricity consumption and averaged outdoor temperature of a household (a sample in Beijing)

Based on the above relations, a household can be implemented. For a particular residential community, most popular households have been specified. Input the data of these households into the household model, and typical levels of energy will be calculated. A parametric analysis will create results that indicate the impact of the selected factors on the energy output of the household model. If focused on the technological variables, technological impacts on residential energy at the household level can be obtained.

For a residential community, any one of the variables may vary by a large margin. For example, the external wall could be brick, concrete with or without insulation, and have different insulation. The range of each relevant variable is determined upon the essential data mentioned above. By establishing simulation of a household model with different selected conditions, all possible levels of residential energy per household will be calculated. These levels are compared with the historical data to verify the household model. Eventually, the range of residential energy per household will be identified for a community.

At the community level, local economic conditions and energy policy are used to ascertain the statistical distribution of all households of different energy levels. The energy demand and consumption of a residential community can then be estimated using econometrics method. Analysis at the community level does not involve technological variables, but economic condition plays a sensitive role. The historical residential energy data obtained via social surveys are used to determine the distribution.

Similarly, at the city level, a community can be treated in the same way that a community model handles the household model. Furthermore, at the national level, a national model can use all the possible outputs of the city model as essential elements.

Overall, the household is the basic element of the four-level model. The output of a community model is determined by all possible outputs of households in that community and its distribution. Technological impacts can be analysed at the household level, whereas all other relevant variables are isolated.

Conclusions

Predicting energy demand is necessary for energy production planning, and associated environmental impact assessment purposes. It obviously requires a large-scale co-ordinated survey, statistical analysis, and technology impact simulation work. We have proposed a four-level model framework for such an ambitious undertaking, and began by focusing on technology impact analysis in the household level model. For the household model, computer simulations that embrace a number of practical energy efficient building envelope and climatic control technologies are being performed (Liao 2001). The results can be easily incorporated into a community model to examine the actual impact of various EET's on the regional level.

Acknowledgement

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