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System dynamics modeling for urban energy consumption and CO_2 emissions: A case study of Beijing, China

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ABSTRACT

It is clear that city must be part of the solution if an urbanizing world is to grapple successfully with ecological challenges such as energy depletion and climate change. A system dynamics model was developed in this study using STELLA platform to model the energy consumption and CO_2 emission trends for the City of Beijing over 2005–2030. Results show that the total energy demand in Beijing is predicted to reach 114.30 million tonnes coal equivalent (Mtce) by 2030, while that value in 2005 is 55.99 Mtce, which is 1.04 times higher than the level in 2005. Accordingly, the total CO_2 emissions in 2030 will reach 169.67 million tonnes CO_2 equivalent (Mt CO_2-eq), 0.43 times higher than that of 2005. The change of energy structure from carbon rich fuel as coal to low-carbon fuel as natural gas will play a very essential role in carbon emission reduction activities of Beijing. The modeling results also shows that the service sector will gradually replace the industrial dominant status in energy consumption as the largest energy consuming sector, followed by industrial and transport sector. The sensitive analysis suggests that change of economic development mode and control of rational population growth will have a far-reaching influence on energy consumption and on carbon emissions. All these results will provide essential information for Beijing's future energy and carbon emission profiles.

1. Introduction

More than one-half of the world's population now lives in urban areas, but they are blamed for producing as much as 80% of humanity's greenhouse gas (GHG) emissions. In China, for instance, the 35 largest cities contain about 18% of the country's population and contribute to 40% of the country's energy usage and CO_2 emissions in 2006 (Dhakal, 2009). Therefore, they have played crucial roles in determining the energy and carbon emission profiles of the nation, and would be of great significance in achieving the country's national targets such as energy security and climate change mitigation (Zhang et al., 2011a,b; Chen and Chen, 2012; Li et al., 2010a; Zhang and Hu, 2011; Cai et al., 2009b). Systematic analysis and dynamic modeling of urban energy demand and carbon emissions are extremely important to understand and address issues associated with fuel security, energy system planning and management, growth of GHG, and other emissions and investment decisions (Akimoto et al., 2008; Vera and Langlois, 2007; Liu et al., 2009; Cai et al., 2009a). However, it is challenging to achieve the desired prediction accuracy, because cities are dynamic systems of organized complexity, with multiple independent variables that all affect each other. A variety of factors associated with economic development, population growth and migration, climate change, and even consumer behavioral patterns need to be considered simultaneously in a simulation model. Thus, energy demand forecasting at different temporal and spatial scales must fully account for varying levels of system complexity.

In the past decades, a number of studies were conducted for planning energy management systems and controlling the associated pollution gas and GHG emissions at the city level, with the classical energy-modeling approaches which can be categorized into three types: top-down (Lu et al., 2010; Xu and Masui, 2009), bottom-up (Phdungsilp, 2010; Gielen and Chen, 2001; Lin et al., 2010; Kanudia and Loulou, 1998; Cormio et al., 2003; Zhang et al., 2011a; Feng and Zhang, 2012), and hybrid models (Bohringer and Rutherford, 2009; Liu et al., 2011; Hadley and Short, 2001; Turton, 2008; Mirasgedis et al., 2007). Traditional energy models applied to the previous studies usually use deterministic forecasts under assumption that we can precisely foresee the evolution of the energy system. Most of them run with the aid of scenario analysis as a snapshot that describes a possible and plausible future, making it difficult to adequately manage the dynamical evolution and the intrinsic stochastic behavior of many vital elements inside the urban energy system. In this context, system dynamics (SD) can be adopted to describe the inner interactions and structures impacting urban development and identify the desirable and undesirable

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interventions, thus capable of illuminating the evolving process and predicting the energy development trend of the whole city.

This study explores the intrinsic relationship between energy demand and economic and social environment, which helps forecast municipal energy demand and carbon emissions in a fast growing urban region. Taking the city of Beijing as a case, an integrated system dynamics model was developed with a coupled modeling structure based on the framework of STELLA software, which offered a realistic platform for predicting the trends of Beijing's energy demand and CO_2 emissions from 2005 to 2030. The SD model will hopefully improve our understanding on the inherent inter-linkages and dynamic evolutionary structures impacting future urban energy system development, and identify the significant contributors to urban energy demand and carbon emissions. Such information is necessary for Beijing's future energy planning and guidelines for policy-making, and highlights possible suggestions for urban energy conservation and carbon emission reduction.

2. Study area and methodology

2.1. Overview of the study area

Beijing is the capital of China which is located on the northwest border of the North China Plain and is surrounded by Yanshan Mountain in the west, north and northeast. Beijing occupies an administrative area of around 16,808 km^2, comprising of 16 districts and 2 counties (Dong et al., 2012). Similar to other metropolises in developing countries, Beijing is undergoing rapid transformation, with a growing population, many new buildings, and increasing automobile traffic. In 2010, Beijing's GDP increased 10.3% compared with the previous year, reaching 1411.36 billion Chinese Yuan (CNY), and the per capita GDP was 71,938.43 CNY. The population of Beijing exceeded 19.61 million with the floating population accounting for 35.89%, and the civil motor vehicle fleet exceeded 4.80 million units (including 3.74 million privately owned vehicles) at the end of 2010 (BMSB, 2011). The Beijing metropolis is also characterized by a scarcity of natural resources, demonstrated by the fact that all of the natural gas and crude oil consumed by the city, as well as 95% of the coal, 64% of the electricity, and 60% of the refined oil consumed has to be imported from outside (Li et al., 2010b). Along with the rapid economic and social development, Beijing has witnessed manifold increase in the energy consumption and related carbon emissions in the last three decades. In 2010, the total energy consumption reached 69.54 Mtce and, correspondingly, the per capita energy consumption was 3.54 tce, 1.5 times the national average, ranking second amongst Chinese cities, only inferior to Shanghai (NBS, 2011). The high levels of energy consumption have, in turn, resulted in high carbon emissions. The per capita CO_2 emissions reached 6.91 tonnes in 2009, i.e., 1.3 times the national average.

It is worthwhile to note that Beijing is the most representative city experiencing the rapid urbanization and economic growth, the accelerated changes in technology, lifestyle, and societal transformation, as well as increasing energy consumption and carbon emissions. For this reason, we chose Beijing as the case area for dynamic modeling of urban energy consumption and CO_2 emissions.

2.2. Concept of system dynamics

System dynamics (SD), introduced by Jay Forrester in the 1960s, is a well-established system simulation methodology for understanding, visualizing and analyzing complex dynamic feedback systems (Zhao et al., 2011). In light of systems thinking, we can analyze the cause-and-effect relationship among the factors inside the system and depend on the computer simulation to quantitatively analyze the structure of the information feedback system and the dynamic relation between function and behavior. SD is robust in that it could reflect the driving forces, incorporate individual subsystems into a general framework and analyze their interactions, thereby providing holistic understanding of the whole system as well as the relevant policy responses for urban sustainability (Yuan et al., 2008). However, it suffers from the shortcoming that all the input data necessary for the operation of SD model need external generation.

In fact, SD has been applied extensively to many areas including social-economic systems (Forrester, 1969, 1971), ecological systems (Saysel and Barlas, 2001), transport systems (Suryani et al., 2010), environmental management and policy assessment, such as solid waste management (Dyson and Chang, 2005), water resource management (Stave, 2003; Rehan et al., 2011), GHG mitigation (Anand et al., 2005; Kunsch and Springael, 2008), sustainable evaluation and environmental planning (Guo et al., 2001). Within the energy management regime, SD models have been developed and applied to national energy policy evaluation (Ford, 1983; Naill, 1992; Qudrat-Ullah, 2005), energy efficiency analysis (Dyner et al., 1995), and the development of energy industry (Bunn and Larsen, 1992; Chi et al., 2009). To the best of our knowledge, not much attention has been paid to the research of urban energy and carbon emissions from the perspective of system dynamics.

It is important to note that the software Vensim® and Stella® are widely adopted by system dynamics models for simulation applications, which provide a user-friendly interface. In addition, they offer a flexible way to dynamically visualize and communicate how complex systems and ideas really work by building a variety of simulation models from causal loops or stock and flow (Isee System, 2006). In this study, the software package Stella® was employed to the model building of urban energy consumption and related carbon emissions.

2.3. Formulation of the Beijing-STELLA Model

In this study, a system dynamics based computer simulation model was developed, which has been named as Beijing-STELLA Model, for estimation and prediction of urban energy consumption trends and CO_2 emissions in Beijing. The boundary of the Beijing-STELLA Model is the total administrative area of Beijing City. The concerned period for the dynamic modeling is from 2005 to 2030. In light of the research target and data availability, the structure of Beijing-STELLA Model was designed as a compound of six sub-models, i.e., socioeconomic, agricultural, industrial, service, residential, and transport sub-models. The stock-flow diagram for the model is shown in Fig. 1.

It should be emphasized that it is impossible to describe the dynamics of socio-economic processes by a single empirical equation or classical formula as that in biological or ecological areas due to complexity of socio-economic issues. With regard to this, a set of empirical equations were developed based on different combinations of input variables for various sub-models. Real-world data relevant to various internal linkages among socioeconomic and managerial factors were processed to retrieve regression analyses performed using the SPSS statistical software (SPSS Inc., Chicago, IL) that support flows and conditions within and among these six sub-models. The regression equation can be expressed as follows:

$$Y = f(X_1, X_2, \ldots, X_n) \tag{1}$$

where X is the independent variable, Y is the dependent variable, and the simulation error rate μ_i for every value of Y (Y_i) is given by

$$\mu_i = \left| \frac{(Y_i - A_i)}{A_i} \right| \tag{2}$$

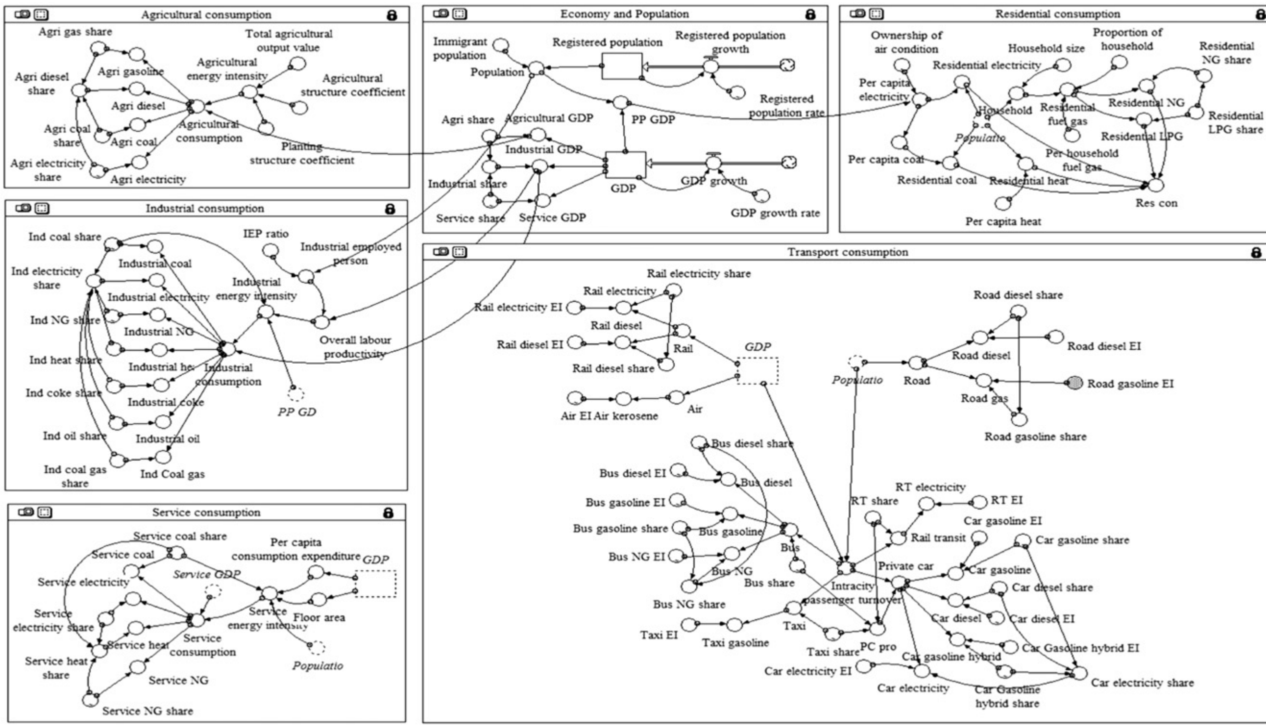

Fig. 1. The stock-flow diagram of Beijing-STELLA Model.

where A_i represents the actual value and Y_i is the simulated value.

Among the alternatives, the best regression equations were selected according to two criteria, i.e., the equation has to be logical (i.e., it has to provide a causal explanation for an observed trend), and it needs to have a high goodness of fit (i.e., R^2) (Lei and Wang, 2008). In addition, the energy consumption data from 2006 to 2010 was reserved for later model validation, and the verification results are shown in Appendix B. Most of the data used in this paper were collected from Beijing Statistical Yearbook, China Energy Statistical Yearbook, and the survey data of government departments, including Beijing Development and Reform Commission, Beijing Transportation Bureau, Beijing Statistical Bureau, and National Energy Administration of China. The modeling details of subsystems are described in the following sub-sectors, and the main variables and the final regression equations used in this model are described in Appendix A.

2.3.1. Socio-economic sub-model

Socio-economic sub-model is the core of Beijing-STELLA Model, having interactions with all other sectors. As a rule of thumb, economic growth is closely related to growth in energy consumption because the more energy is used, the higher the economic growth. Thus, assumptions concerning economic development will definitely affect the estimation result of energy demand and CO_2 emissions. The 12th Five-Year Plan (FYP) of Beijing envisions that Beijing's economic growth rate during 2011–2015 will be about 8%, and according to the WEO (2008), China is assumed to grow at 9.2% per year between 2006 and 2015 and at 6.1% between 2006 and 2030. As Beijing is one of the most developed cities in China and its economic growth rate is higher than the national average, we assume that the GDP in Beijing will grow at a rate of 8% during 2011–2020 and 6% during 2021–2030. Considering the trend of recent years and the outline perspective plan of Beijing, most of GDP in 2030 will be contributed by the service sector, which accounts for 85%, while the remaining come from agricultural (1%) and industrial (14%) sector.

Population scale is another essential factor that affects the size and composition of energy demand, directly and indirectly through its impact on economic growth and development (WEO, 2008). The total population in Beijing can be divided into the registered permanent population and the floating population. Due to the large demand for cheaper labors and relative higher salary compared to rural areas in cities, Beijing without exception will experience the ever increasing population in China, among which the high net immigration rate is the dominant contributor (Yuan et al., 2008). In contrast, the registered permanent population will be strictly controlled by local government, which is predicted to reach 14.82 million in 2030 according to the 12th FYP of Beijing. The floating population was predicted by Logistic Equation based on the historical data from 1978 to 2005, the maximum capacity of which was assumed to be no more than 15 million, considering the carrying capacity of the urban resources and the environment through expert consultations.

2.3.2. Industrial sub-model

Like many other megacities in Asia, Beijing is relocating its major industries either to peri-urban areas or to areas outside city borders, leaving cities increasingly dominated by the tertiary sector. Consequently, the proportion of the industrial energy consumption in Beijing has been declining dramatically, accounting for less than half of the total consumption since 2005. In this study, construction sector was also included in this sub-model. Industrial energy consumption was calculated as follows:

$$ED_{\mathrm{I}} = EI_{\mathrm{I}} \times VA_{\mathrm{I}} \quad (3)$$

where ED_{I} is the energy consumed by the industrial sector; EI_{I} is the energy consumption per unit of industrial sector value added; VA_{I} is the value added of industrial sector.

Energy intensity, measured as energy consumed per unit of industrial value added, is a key indicator determining industrial energy consumption. Industrial energy intensity is closely related to economic development and technology innovation. The industrial energy structure, described by the share of raw coal in total energy consumption, also makes a significant sense to the energy intensity. By using regression technique on 1995–2005 data, the indicator of industrial energy intensity was formulated (see Appendix A). Different types of energy carriers were distinguished, i.e., solid fuels (coal product), liquid fuels (petroleum product), gaseous fuels (natural gas), electricity and heat. The proportions of coal, natural gas and electricity were estimated in consideration of historical trends, government and special-sector planning documents, taking the energy structure of OECD countries for reference as well.

2.3.3. Service sub-model

Following a similar modeling framework, energy consumption in the service sector was determined by the value added and energy intensity of the service sector:

$$ED_S = EI_S \times VA_S \quad (4)$$

where ED_S is the energy consumed by the service sector; EI_S is the energy consumption per unit of service sector value added; VA_S is the value added of service sector.

The energy use of the service sector is dominantly driven by the population, the commercial floor area growth, energy structure and the per capita consumption expenditure. GDP was not used as a direct driver but rather as a force that drove the floor area growth and the per capita consumption expenditure. In this study, the floor area was expressed as the sales area of commercial space due to the lack of data. A regression was performed on 1995–2005 data for the energy intensity of service sector (see Appendix A). There are four major sources of energy in this sector, including coal, natural gas, electricity and heat. The proportion of each fuel type was obtained through the use of curve-fitting to historical trends based on the data from 1995 to 2005.

2.3.4. Residential sub-model

The rapid growth of the economy has not only led to dramatic changes of wealth, but also lifestyle and energy consumption. Changing lifestyles and the rising living standard have resulted in rapid growth in the energy consumption of domestic sector, with the per capita residential energy consumption increasing from 0.35 tce in 2000 to 0.63 tce in 2010. Similarly, the residential energy demand can be defined as:

$$ED_R = \sum_j EI_R \times AL_R \quad (5)$$

where ED_R is the residential energy consumption; j is the energy type; EI_R is the residential energy consumption per capita or per household; AL_R is the total population or the number of households.

The main energy types consumed in the residential sector are electricity, fuel gases (natural gas and LPG), coal and heat. Electricity use per capita was highly correlated with the stock of electrical appliances and GDP per capita. The growth of household electrical appliances of Beijing was considered as a function of per capita GDP. Residential coal consumption was negatively correlated with the electricity use (see Appendix A). Besides, heat consumed per capita and fuel gases consumed per household have remained almost unchanged at 47.12 kgce and 280.53 kgce, respectively. The goal of the Beijing government of promoting natural gas application is ambitious, i.e., 100% of the urban households will be connected to natural gas by 2015.

2.3.5. Transport sub-model

The transport sector in this study was divided into four sub-sectors, including railway, highway, airway, and intracity passenger transport which was then split into public transit and individual traffic. Energy demand in the transport sector was modeled as a product of activity level, structure and energy intensity, as shown in the following equation:

$$ED_T = \sum_i TT \times MS_i \times FE_i \times CC_i^{-1} \quad (6)$$

where ED_T is the energy consumption from the transport sector; i is the transport mode; TT is the freight or passenger traffic turnover; MS_i is the mode split of traffic turnover; FE_i is the oil consumption per unit distance; CC_i is the carrying capacity.

In general, there are two factors that affect the transport demand including macroeconomic condition (GDP growth), and demographic factor (population). Transport turnover was estimated by extrapolating the historical trend from 1994 to 2005 through regression analyses, where the turnover volume was regarded as the explained variable, and population and GDP were the explanatory variables (see Appendix A). According to the historical technical data and existing condition analysis, energy intensities (energy consumed per passenger-kilometer/ton-kilometer) in railway and highway transport sub-sector will not be improved much in the near future, which was assumed to be constant in this model. Besides, the fuel efficiency of vehicles in intracity transport would increase by 20% during the study period with reference to international advanced level. The modal share was estimated according to the government's development strategy which assumes that the contribution of mass transit to passenger capacity will reach 62% in 2030.

2.3.6. Agricultural sub-model

The agricultural sector is comprised of farming, forestry, animal husbandry, and fishing. Energy consumption from the agricultural sector was calculated using the following equation:

$$ED_A = EI_A \times VA_A \quad (7)$$

where ED_A is the energy consumed by the agricultural sector; EI_A is the energy consumption per unit of agricultural sector value added; VA_A is the value added of agricultural sector.

It is important to note that the proportion of energy consumed by agricultural sector is relatively small, about 1.5% of the total consumption in Beijing. The energy consumption per unit of GDP has decreased by 40% over the past decade, which can be attributed to the improvement of machinery and equipment, the optimization of agricultural structure, and changes in the structure of agricultural products. Coal, oil and electricity are three major sources of energy in this sector. A multiple linear regression model was developed to relate agricultural energy intensity to the total agricultural output value and agricultural structure, based on the data from 1995 to 2005 (see Appendix A).

2.3.7. CO_2 emissions

The projected CO_2 emissions were estimated based on the energy demand and the carbon emission factors. The CO_2 emission factors for different energy types were taken from the corrected value based on the 2006 IPCC recommended method (Dhakal, 2009; Bi et al., 2011). Carbon emissions from electricity and heat were allocated to the primary energy including coal and natural gas based on the conversion efficiency of power generation and heating (NBS, 2011). CO_2 emissions were calculated using the following equation:

$$CE = \sum_{i,j} ED_{i,j} \times EF_j \quad (8)$$

where CE is the total carbon emissions of the whole city; i is the sub-sector; j is the energy type; $ED_{i,j}$ is the energy consumed by sub-sector i in energy type j; and EF_j is the carbon emission factor of energy type j.

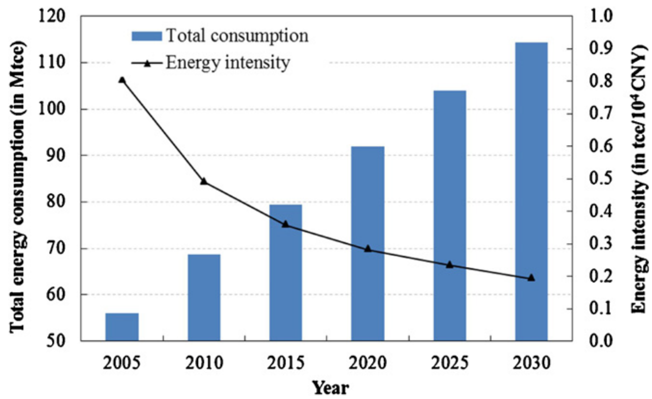

Fig. 2. Total energy consumption and energy intensity in Beijing from 2005 to 2030.

3. Results and discussion

3.1. Energy consumption

3.1.1. Overall energy consumption

The values of modeling results by Beijing-STELLA Model from 2005 to 2030 are shown in Fig. 2. Along with the intensified urban development and expanding population, the total energy consumption in Beijing is predicted to increase steadily from 55.99 Mtce in 2005 to 114.30 Mtce in 2030, with an annual growth rate of 2.90%. However, the energy consumption intensity, measured by consumption per unit GDP, will reduce from 0.80 tce/10,000 CNY in 2005 to 0.19 tce/10,000 CNY in 2030, with an average annual decreasing rate of 5.56%. Beijing will make tremendous achievements in the improvement of energy efficiency, although it does not achieve a real decline in total energy consumption. Moreover, the modeling result for 2015 shows that about 26.98% reduction of energy intensity can be achieved compared with the 2010 level, while the target of Beijing's 12th FYP is to reduce energy intensity by 17%.

3.1.2. Sectoral energy consumption

The share of total final energy consumption by different sectors is presented in Fig. 3. In 2005, industrial sector contributed to the major share (53.38%) of the final energy consumption, followed by the service sector. During the period from 2005 to 2030, however, the service sector will gradually replace the industrial dominant status and become the largest energy consuming sector, reaching the proportion of 42.37% in 2030. The transport sector also deserves attention paid to it, since it is likely to confront a large increase in energy consumption resulting from fast growth of private vehicles. In 2021, the transport sector will account for 19.09% of the total final energy consumption, a 6.74% increase over the level of the year 2005. Nevertheless, the share of energy consumed in the transport sector will basically maintain stable after 2021 due to the traffic modal shift and the improvement of vehicle fuel efficiency. The absolute energy consumption of the residential sector also shows an upward trend with an annual growth rate of 3.26%, while the share will remain more or less unchanged from 2005 to 2030.

3.1.3. Energy mix

The structural changes of energy consumption from 2005 to 2030 are shown in Fig. 4. It is apparent that the energy usage structure in Beijing will experience a tremendous change. In 2005, coal and oil were the primary fuels in the final energy consumption system, with the proportion of 39.55% and 29.56%, respectively. Along with the optimization of energy structure, in 2030, the proportion of coal consumption will decrease to 6.87%, while the clean energy usage, including electricity and natural gas, will increase rapidly, reaching a total of 52.92%, nearly 2.39 times higher than the 2005 value. It is also worthwhile to note that the share of oil consumption will decline since 2015. Overall, the energy usage structure will be further optimized, with rapid growth in the use of alternative clean energy. This, in turn, will play an important role in the mitigation of carbon emissions (see Section 3.2).

3.2. CO_2 emissions

3.2.1. Overall CO_2 emissions

Presented in Fig. 5 are the total CO_2 emissions in Beijing from 2005 to 2030. On the whole, the total CO_2 emissions show an increasing trend, yet with a slight drop between 2011 and 2015. The total emissions will increase from 118.41 Mt CO_2-eq in 2005 to 169.67 Mt CO_2-eq in 2030, with an annual growth rate of 1.45%. The growth rate of carbon emissions is much lower than that of energy

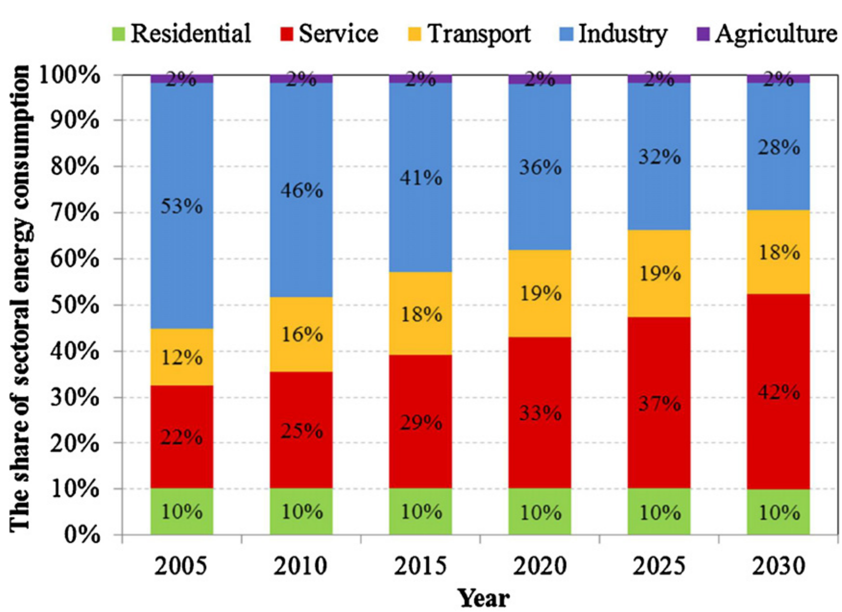

Fig. 3. Structure of final energy consumption by sector in Beijing from 2005 to 2030.

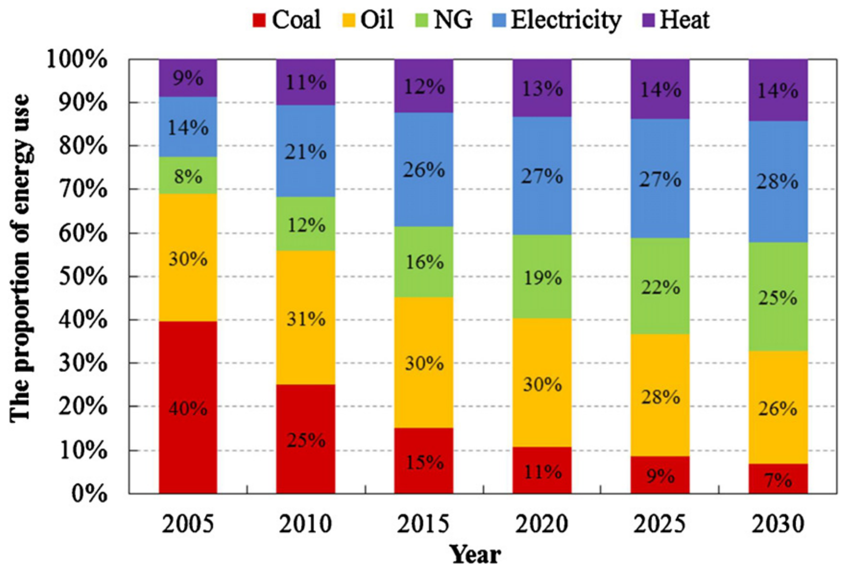

Fig. 4. Final energy mix in Beijing by fuel type from 2005 to 2030.

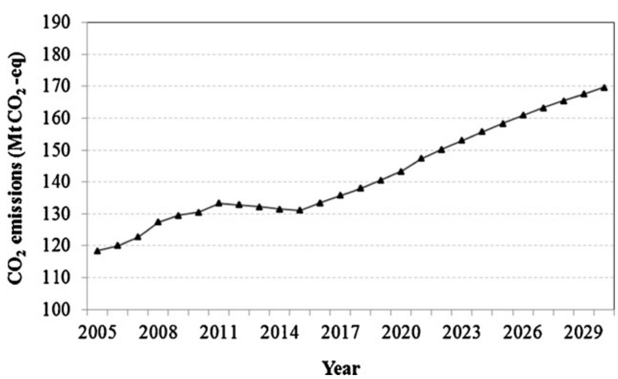

Fig. 5. Total CO_2 emissions in Beijing from 2005 to 2030.

consumption, which is probably due to the optimization of the energy structure, i.e., the increasing proportion of low-carbon fuels. The evident decline of carbon emissions during the period from 2011 to 2015 is attributable to the two facts, i.e., (1) Beijing municipal government will continuously eliminate backward production capacity, e.g., the coking production capacity, which will decline sharply due to the steel works-Shougang Group moving to Tangshan City; (2) Beijing has made significant efforts to improve energy efficiency by developing thermal power plants with high capacity and performance and phasing out smaller plants. The construction of "Four Major Thermoelectric Centers" will be accelerated during the 12th Five-Year period. This will cause a rapid decrease in carbon emissions in Beijing between 2011 and 2015.

The CO_2 emission intensity of economic activities and per capita CO_2 emission value are shown in Table 1. The emission intensity presents an overall declining trend, with an average annual rate of 6.83%. The per capita carbon emissions will decrease steadily from 7.67 t CO_2-eq in 2005 to 5.85 t CO_2-eq in 2020, but then rise slightly afterward, reaching 6.00 t CO_2-eq in 2030. In the short time, the adjustment of industrial structure and the optimization of energy structure will make a big difference in reducing per capita emissions. However, to realize the long-term reduction goal, more strict control of the total energy consumption growth is still essential. Reports show that the per capita emission levels of China, the United States, Australia, and the EU-27 countries were 6.8 t CO_2-eq, 16.9 t CO_2-eq, 18.0 t CO_2-eq, and 8.1 t CO_2-eq in 2010, respectively (IES-JRC, 2011). Although Beijing's per capita carbon emissions are a little higher than the national average, they are still significantly lower than those of the United States and many developed countries, but relatively close to those of Europe.

Table 1
CO_2 emission intensity and per capita CO_2 emissions of Beijing.

	CO_2 emission intensity (t CO_2-eq/10^4 CNY)	Per capita CO_2 emissions (t CO_2-eq)
2005	1.70	7.67
2010	0.93	7.12
2020	0.44	5.85
2030	0.29	6.00

3.2.2. Emission contributor analysis

The share of sectoral contribution in total emissions from 2005 to 2030 is shown in Fig. 6. Among all of the sectors, the industrial sector contributed the largest share of CO_2 emissions at 42.09% in 2005, followed by the electricity and heating generation (i.e., transformation) sector. With the continuous adjustment of the industrial structure, the emission contribution of industrial sector will gradually decrease to 24.51% in 2030. In contrast, the CO_2 emissions from the transport sector will experience a quick growth rising from 10.79% in 2005 to 24.52% in 2030 due to the rapidly increasing vehicle stock, making the transport sector another dominant contributor to overall emissions. The emissions of the service sector will account for 15.98% of the total in 2030, much lower compared to its share in energy consumption, owning to the dominance of relative clean energy type (electricity and natural gas) consumed in this sector.

The detailed break down of absolute CO_2 emission growth for Beijing during the period from 2005 to 2030 is presented in Table 2. It can be found that the industrial sector will achieve absolute cuts in emission level, which will definitely ease the burden of urban carbon emissions. In contrast, the transport sector will become the largest contributor to the absolute emission growth, followed by service and transformation sector. In light of identification of key sectors for carbon emission reduction, the transport, service, electricity and heating generation sectors are the ones, due to their contribution or potential contribution to total emissions.

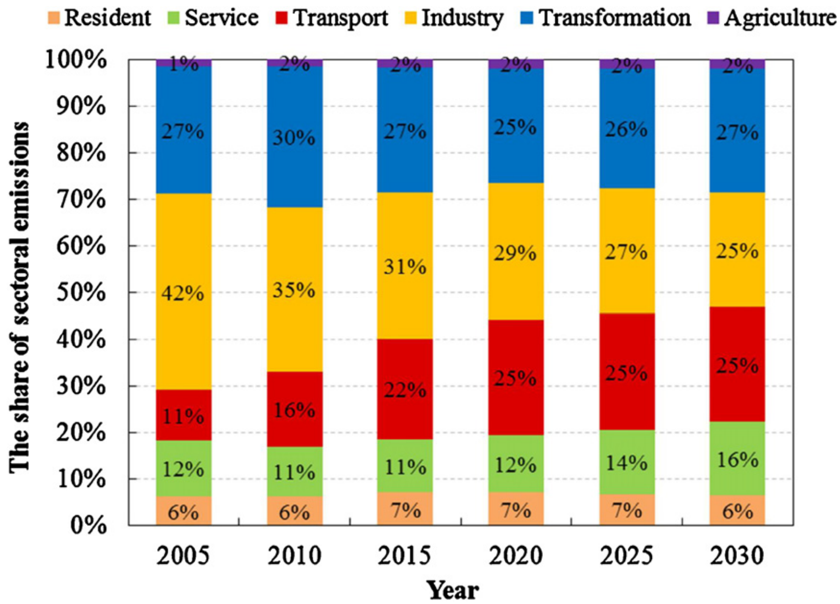

Fig. 6. Structure of CO_2 emissions by sector in Beijing from 2005 to 2030.

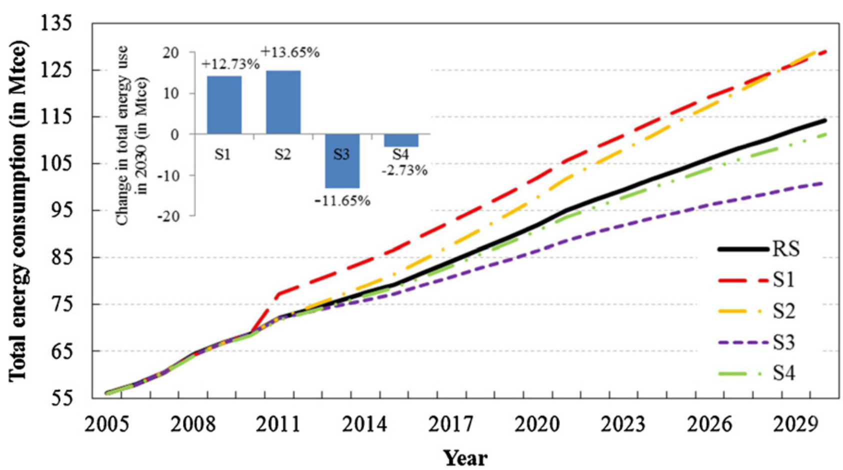

Fig. 7. Sensitivity analysis of energy demand in response to macroeconomic drivers.

3.3. Sensitivity analysis

To examine the system's responses to variations of input parameters, a series of sensitivity analyses have been conducted in our study. Since the demographic and economic factors are the key drivers of urban energy consumption and carbon emissions underpinning all the producing and consuming sectors, three variables were chosen for sensitivity analysis including population, GDP growth rate and the share of service sector in this study, and five scenarios were designed namely reference scenario (RS), +25% population growth rate (S1), +25% GDP growth rate(S2), −25% GDP growth rate (S3) and 90% share of the service sector by 2030 (S4). The results of the sensitivity analysis are presented in Fig. 7.

The results show that the economic growth and population have significant effects on the changes in energy consumption in Beijing. In particular, increasing the GDP growth rate by 25% results in a 13.65% higher total energy consumption in 2030. Therefore, it is necessary to change the mode of economic growth and seek

Table 2
Sectoral emission analysis of Beijing.

Sector	Absolute emission growth from 2005 to 2030 (Mt CO_2-eq)	Sectoral contribution to the absolute emission growth (%)	Sectoral emission growth rate (%)
Agriculture	1.76	3.43	2.87
Industry	−8.24	−16.07	−0.72
Service	12.75	24.87	2.57
Residential	3.52	6.87	1.58
Transport	28.84	56.26	4.84
Transformation	12.63	24.64	1.33
Total	51.26	–	1.45

coordinated development for economic growth and energy conservation. In terms of the demographic factor, Beijing has experienced a booming population in recent decades, which has brought serious problems including tight water supplies, surge in vehicles and traffic jams, especially excessive energy consumption. The control of urban population will be another important task for achieving the sustainable development of Beijing, especially with a reasonable proportion of floating population. It can also be found from Fig. 7 that the improvement in the share of service sector does not have prominent impact on total energy consumption. Beijing has made great achievements in the optimization of industrial structure, along with the high development of service sector, so energy saving by structure adjustment will be limited in the future. The above factors have similar effects on the total CO_2 emissions, which will not be discussed in detail repeatedly.

4. Conclusions

In order to project the energy demand and CO_2 emissions in Beijing over 2005–2030, an integrated system dynamics model was developed based on the framework of STELLA software, which would definitely provide quantitative base for effective urban energy planning and management as well as alternative scenarios for the development of a low-carbon city. The modeling results show that Beijing is to be confronted with a heavy burden of energy supply and carbon mitigation, which will stress the urgent need for energy savings and emission reductions. Particularly, the total energy consumption in Beijing is predicted to reach 114.30 Mtce in 2030, 1.04 times higher than that of 2005. Correspondingly, the total CO_2 emissions present a general increasing trend which will be 0.43 times higher than that of 2005, in despite of a slight drop between 2011 and 2015.

In terms of the final energy structure, the optimization from carbon rich fuel as coal to low-carbon fuel as natural gas will play a very essential role in carbon emission reduction activities of Beijing. However, it should also be remembered that the reduction potential by readjusting energy structure is very limited.

This study also shows that the service sector will gradually replace the industrial dominant status in energy consumption as the largest energy consuming sector, followed by industrial and transport sector. In terms of carbon emissions, the transport sector will become the main contributors together with transformation and industrial sectors. Therefore, the service and transport sectors are identified as promising fields for achieving effective control of energy consumption and carbon emissions over the next few decades.

The sensitive analysis demonstrates that appropriate controls of economic development and population growth will have a far-reaching influence on urban energy conservation and on carbon mitigation in Beijing.

Nevertheless, a number of refinements and model extensions are required for future consideration: (1) the framework in modeling interactions between socioeconomic factors and energy demand in various sectors are highly aggregated, which may require the inclusion of some disaggregated schemes to describe the agent behaviors and internal dynamics in finer detail; (2) in this study, only macro economic factors were considered for sensitivity analysis. If the different sensitivity analyses can be conducted at the sectoral level, the results will become more robust and reliable for sustainability policy making.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2012.09.008.

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