Urban energy consumption and CO_2 emissions in Beijing：Current and future

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Abstract

This paper calculates the energy consumption and CO_2 emissions of Beijing over 2005-2011 in light of the Beijing's energy balance table and the carbon emission coefficients of IPCC. Furthermore, based on a series of energy conservation planning program issued in Beijing, the LEAP-BJ model is developed to study the energy consumption and CO_2 emissions of Beijing's six end-use sectors and the energy conversion sector over 2012-2030 under the BAU scenario and POL scenario. Some results are found in this research: (1) during 2005-2011, the energy consumption kept increasing, while the total CO_2 emissions fluctuated obviously in 2008 and 2011. The energy structure and the industrial structure have been optimized to a certain extent. (2) If the policies are completely implemented, the POL scenario is projected to save 21.36% and 35.37% of the total energy consumption and CO_2 emissions than the BAU scenario during 2012 and 2030. (3) The POL scenario presents a more optimized energy structure compared with the BAU scenario, with the decrease of coal consumption and the increase of natural gas consumption. (4) The commerce and service sector and the energy conversion sector will become the largest contributor to energy consumption and CO_2 emissions, respectively. The transport sector and the industrial sector are the two most potential sectors in energy savings and carbon reduction. In terms of sub-scenarios, the TEC is the most effective one. (5) The macro parameters, such as the GDP growth rate and the industrial structure have great influence on the urban energy consumption and carbon emissions.

***Keywords**: Urban; Energy consumption; CO_2 emissions; Scenario analysis; LEAP model*

1. Introduction

Cities play a more important role in the energy consumption of China in recent years with its accelerating urbanization (Steemers 2003; Zhang 2005). The 35 largest cities containing 18% of the populations cause 40% of China's energy use (Dhakal 2009). The cities' total energy consumption is stepping up along with the rapid economic growth in the future. In addition, CO_2 caused by energy consumption is a major source of greenhouse gases (IPCC 2006, 2007) and CO_2 emissions in China accounted for 29% of total global CO_2 emissions (Olivier et al. 2013). Climate change resulted from GHG emissions can cause significant negative effects on both natural and socio-economic systems (Solomon et al. 2009), so enormous advances in energy technology are needed for every country to stabilize atmospheric carbon dioxide concentrations at an acceptable level (Roger et al. 2008), especially in the emerging developing countries. Thus, in terms of energy security and mitigation to climate change，urban energy conservation and CO_2 emissions reduction has already been a crucial problem in China. On the other hand, a better understanding of urban energy consumption and CO_2 emissions will be beneficial to make a much needed integrated framework and policies for solving urban development, energy, and climate change issues (Dhakal 2009).

There are some researches about urban energy consumption and CO_2 emissions (Bi et al. 2011; Rutter and Keirstead 2012； Arnold and Barth 2012). Gomi et al. (2010) developed the local (city-scale) low-carbon scenario and proposed a model based on the ‘‘export-base’’ approach of standard regional economics. In regard of energy demand and GHG emissions, they were assessed using the Extended Snapshot tool (ExSS), only considering GHG emissions from consumption of fossil fuels and activities conducted within the area of Kyoto city. They estimated the countermeasures to achieve the low-carbon target of Kyoto city and showed a quantitative and consistent future snapshot. Cai et al. (2013) made a comparative study of economy structure, energy supply and carbon emissions among a few cities especially between Beijing and London from the views of geographic location, climate and population status. Phdungsilp (2010) applied LEAP model to study the options for energy and carbon development for the city of Bangkok by simulating a range of policy interventions. Sixteen proposed scenarios were analyzed using a multi-criteria decision-making approach. The local air pollutants or emissions were analyzed at the source. Parshall et al. (2010) used the Vulcan data to measure the energy consumption and related CO_2 emissions in urban areas in United States. They also highlighted the methodological challenges of this type of analytical exercise and summarized alternative approaches. As for energy-related CO_2 emissions, all direct emissions sources located within the geopolitical boundary of the local government were focused. Similarly, a number of studies focus on China’s urban energy consumption and CO_2 emissions (Dhakal 2009; Li et al. 2010; Xi et al. 2011).

The modeling approaches used to estimate future energy demand and CO_2 emissions can be classified into three categories: bottom-up, top-down and hybrid models. Top-down models examine the broader economy and incorporate feedback effects between different markets triggered by policy-induced changes in relative prices and incomes. They generally do not provide technological details of energy production or conversion. As a result, conventional top-down models cannot easily incorporate different assumptions about how discrete energy technologies and costs will evolve in the future. On the contrary, bottom-up models can describe current and prospective technologies in detail, suited to analyze specific changes in technology or policies such as efficiency standards (Bohringer and Rutherford 2009). The Long-range Energy Alternatives Planning System (LEAP) is a bottom-up scenario-based energy/environment modeling tool which is developed by the Stockholm Environment Institute and the Tellus Institute (SEI 2011). It includes energy supply, energy conversion and final energy demand, and aims to project national or regional energy supply and demand and calculate the air pollutants and GHG emissions in the process of energy use and conversion in the medium and long term. Furthermore, it allows analysis of technological specifications and end-use details.

Since LEAP model can be used to set the parameters and model structures according to the characteristics of problem and the availability of data (Zhou et al. 2004), it is widely used to forecast future patterns, identify potential problems and estimate the possible impacts of energy policies on various areas at the global, national, local and sectoral scales (Lin et al. 2010; Cai et al. 2008; Limmeechokchaia and Chawana 2007). In the global level, de la Rue de Can and Price (2008) projected two scenarios to present the energy consumption and CO_2 emissions of a number of world regions and end-use sectors, such as industry, transport, and buildings. On the national scale, Shin et al. (2005) analyzed the impacts of landfill gas electricity generation on the energy market and the cost of generating electricity and greenhouse gases emissions in South Korea using LEAP model. Additionally, LEAP model is also widely used on the sectoral scale (Huang et al. 2005; Zhang et al. 2007). For example, Wang et al. (2006) assessed the CO_2 abatement potential of China's iron and steel industry from 2000 to 2030 according to cost information. Moreover, a great many of studies are aiming at transport sector (Dhakal 2003; Pradhan et al. 2006; Yu et al. 2013; Zhou et al. 2011). On the whole, LEAP model is relatively rare to be applied in the urban level despite of its widespread use (Lin et al. 2010; Phdungsilp 2010).

With the successive optimization of energy structure and rapid development of tertiary industry, Beijing has become a leading example in China in terms of energy consumption and CO_2 emissions per capita (Cai et al. 2013). Furthermore, Beijing is the capital of China, which makes it significant to study on Beijing's energy consumption and CO_2 emissions in the light of its past development paths, as well as policy assessment on energy conservation and CO_2 emissions reduction. However, a handful of literature has focused on Beijing's energy uses and carbon emissions (Feng and Zhang 2012; Wang et al. 2012; Zhang et al. 2013). For example, Feng et al. (2013) developed a system dynamics using STELLA platform to model the energy consumption and CO_2 emission trends for Beijing over 2005-2030. On the basis of the calculation of Beijing's energy consumption and CO_2 emissions during 2005-2011, this paper intends to apply the LEAP model to evaluate Beijing's energy consumption and CO_2 emissions over 2012-2030 under different scenarios as well as relevant policy measures. It not only predicts the future trends, but also assesses the effectiveness of measures aimed at energy conservation and CO_2 emissions.

To sum up, there are two main aims in this paper. The first is to recognize the past paths of Beijing's energy consumption and CO_2 emissions in the light of Beijing's energy balance table from the Beijing statistical yearbook and the default carbon emission coefficients provided by the IPCC (2006) over 2005-2011. A clear understanding of the history path can help to make decisions about how the energy system will develop in the future. The second but the most important aim is to estimate the future energy consumption and CO_2 emissions of Beijing. Given the planned energy conservation and CO_2 mitigation policies, two possible future scenarios and five sub-scenarios are devised. Dividing into six end-use energy consumption sectors and two energy conversion sectors, we construct the LEAP-BJ model to analyze the future trend of energy consumption and CO_2 emissions in Beijing from 2012 to 2030, with 2011 as the baseline year. The results can simulate the future trend of Beijing's energy consumption and CO_2 emissions, as well as provide some general insights on the effectiveness of measures aimed at energy savings and carbon reduction, which will be beneficial for future energy planning and policy making.

The rest of the paper is organized as follows. Section 2 introduces the investigated area. Section 3 presents the methodology, including the research framework. The results are discussed in Section 4. The final section summarizes the conclusions and policy implications of this work.

2. Investigated area

Beijing (longitude 116° 25′ 29″ E, latitude 39° 54′ 20″ N), the capital of China, is the political and cultural center, and one of the four municipalities directly under the Central Government, shown as in the Fig.1. It covers an area of 16,411km^2 with a total permanent resident population of 20.69 million in 2012. In recent years, Beijing's economy develops rapidly, and the GDP grew from 316.17 billion yuan to 1625.19 billion yuan during the period of 2000-2011, with an average annual growth rate of 16.04%. Accordingly, Beijing's energy consumption increased at a rate of 4.88% during this period. In 2011, the total energy consumption of Beijing has reached to 69.95 million tce. However, due to the internal limitation of energy structure, high energy consumption results in large amounts of GHG. In order to achieve the goal of energy conservation and emissions reduction, Beijing issued a series of policies and measures, such as Energy-Saving in Medium and Long term Special Program, Beijing City's 12th Five-Year Plan of Civil Building Energy Conservation, Beijing City's 12th Five-Year Plan of Energy and Beijing's Task Decomposition of Clean Air Action Plan during 2013-2017, etc.

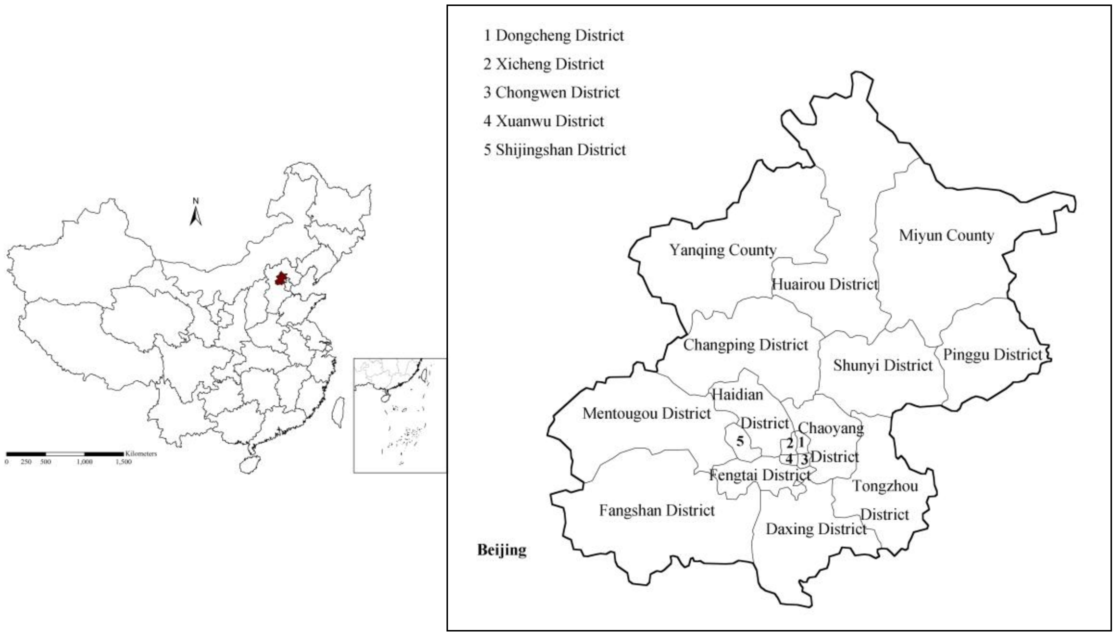


Fig.1

Location of Beijing, China

3. Methodology

3.1 Historical energy consumption and CO_2 emissions

The energy consumption of Beijing during 2005-2011 can be obtained from the Beijing Statistical Yearbook (2006-2012) and the CO_2 emissions are calculated as follows:

$$TE = \sum_{m}\sum_{n} A_{m,n} * NCV_n * C_{m,n} * O_{m,n} * 44/12 \qquad (1)$$

where TE is Beijing's total amount of CO_2 emission from energy consumption; A is the amount of energy consumption; NCV is the net calorific value; C is the carbon emission factor, O is the carbon oxidation rate, the default value of which is 100% in this study; m is the sector, n is the fuel type. Fuel types include the fuel categories in the energy balance tables of Beijing. The CO_2 emissions from end-use sectors and the energy conversion sector are estimated. Six end-use sectors are included: the agriculture sector, the industrial sector, the construction sector, the transport sector, the commerce and service sector and the household sector. The energy conversion sector comprises heat generation and electricity generation.

The net calorific values of various kinds of fuels are from the China Energy Statistical Yearbook (2012). The carbon emission factor is from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Bi et al. 2011; Dhakal 2009; IPCC 2006). In addition, on the basis of the efficiency of processing and conversion and the energy balance table of Beijing in different years, we consider the primary energy (mainly including coal and natural gas) (Fan et al. 2013) when calculating emissions from heat and electricity. Following the territorial principle, emissions from heat and electricity produced inside Beijing are determined without considering those imported (Li et al. 2010). The coefficients of various kinds of energy converted to equivalent of coal are taken from general principles for calculation of total production energy consumption (GB/T 2589-2008).

In the China's energy statistics system, energy consumption in the transport sector does not contain that of vehicles owned by enterprises, institutions and individuals, instead, this part is accounted in the production sectors which the enterprises and institutions belong to, and in the household sector. To match the international definition of energy consumption in the transport sector, we employ the concept of large-scale traffic. Hence, on the basis of each sector's situation, all the gasoline and diesel in household sector, all the gasoline and 35% of diesel in sectors of industry, construction, commerce and service, and all the gasoline in the agriculture sector are included in the transport sector's energy consumption (Wang 2006).

3.2 Model structure and parametric assumption

The time span of the LEAP-BJ model developed in this paper is 2012-2030, with 2011 as the baseline year. The total energy consumption includes energy consumption from end-use sectors and energy transformation (the same with what has been clarified in **Section 3.1**), whose calculation methods are different. The calculation process is introduced as follows (Lin et al. 2010):

Energy consumption of end-use sectors:

In LEAP model, the energy consumption of end-use sectors is calculated by sectors which depend on corresponding activity level and energy intensity using equation (2):

$$EC = \sum_{i}\sum_{j}\sum_{k} AL_{k,j,i} * EI_{k,j,i} \qquad (2)$$

where EC is the total energy consumption of sectors; AL is the activity level; EI is the energy intensity; k is the fuel type; i is the sector; j is the end device/vehicle.

In this paper, activity levels of the agriculture sector, the industrial sector, the construction sector, the commerce and service sector are value added in each sector and the corresponding energy intensities are energy consumption per unit value added; the activity level of household sector is rural or urban population with energy consumption per capita as its energy intensity; the activity level of transport sector[1] is passenger or freight turnover volume and the energy intensity correspondingly is the energy consumption per unit passenger or freight turnover.

Net energy consumption for energy conversion:

$$ET = \sum_{q}\sum_{t}\sum_{p} ETP_{q,t} * (e_{p,q,t} - 1) \quad (3)$$

where ET is the total net consumption for processing and conversion; ETP is the energy transformation product; $e_{p,q,t}$ is the energy consumption of fuel type p to produce unit secondary fuel type t in equipment q; p is the type of primary energy; q is the equipment; t is the type of secondary fuel.

The total CO_2 emissions comprise emissions from end-uses and the energy conversion sector, which are calculated as follows:

CO_2 emissions from end-uses:

$$CEC = \sum_{i}\sum_{j}\sum_{k} AL_{k,j,i} * EI_{k,j,i} * EF_{k,j,i} \quad (4)$$

where CEC are the total CO_2 emissions from end-uses; $EF_{k,j,i}$ is CO_2 emission factor of fuel type k through equipment j in i sector. As for the CO_2 emission in the transport sector, we employ the concept of large-scale traffic, so we also consider emissions from part of the energy consumption in other sectors, as mentioned at the end of **Section 3.1**. In addition, we divide it into two sub-sectors: Freight transport sector and Passenger transport sector which also includes two types of sub-sectors of Public transport sector and Private transport sector.

CO_2 emissions from the energy conversion:

$$ETE = \sum_{p}\sum_{q}\sum_{t} ETP_{q,t} * e_{p,q,t} * EF_{p,q,t} \quad (5)$$

where ETE is the total CO_2 emissions from processing and conversion; $EF_{p,q,t}$ is the emission factor of producing unit secondary energy t from primary energy p through equipment q.

The key parameters in LEAP-BJ model under two scenarios such as population growth rate, GDP growth rate, urbanization rate and share of various industries are shown in Table 1.

[1] Only road transport is considered in the transport sector because of its high influence on total energy consumption and the civil aviation and railway are not included in our study.

Table 1

Assumptions for key parameters in LEAP-BJ model

Key parameters	2011	2020	2030
Population growth rate [a,b] (%)	3.69	3.69	3.69
GDP growth rate [c] (%)	8	6	6
Urbanization rate [d] (%)	86.23	90.00	94.00
Share of agriculture sector (%)	0.8	0.8	0.8
Share of construction sector (%)	4.3	4.3	4.0
Share of industrial sector (%)	18.8	14.0	10.0
Share of commerce and service [c,e] (%)	74.4	80.0	84.0

Note: a. The population is the permanent resident population;

b. The population growth rate is the average annual population growth rate during 1992-2011;

c. The growth rate of GDP and the share of commerce and service are set in the light of Beijing City's 12th Five-Year Plan and the Overall Planning of Beijing Development (2004-2020);

d. The urbanization rate is the proportion of permanent urban resident population accounting for the total permanent residents;

e. The commerce and service sector is the tertiary industry subtracting the transport sector. The transportation, storage and postal industry are treated as a whole in the statistical data, so the value added of transport sector is set to be 33% of the total amount.

3.3 Data and scenarios design

The data used in this work are derived from Beijing Statistical Yearbooks, and relevant urban and sectoral planning, including Beijing City's 12th Five-Year Plan, the Outline of Beijing Traffic Development (2004-2020), the Overall Planning of Beijing Development (2004-2020), Beijing City's 12th Five-Year Plan of Civil Building Energy Conservation, Energy-Saving in Medium and Long term Special Program, Beijing City's 12th Five-Year Plan of Energy and Beijing's Task Decomposition of Clean Air Action Plan during 2013-2017.

Two scenarios: Business As Usual scenario (BAU) and Policy scenario (POL) are designed to assess the effectiveness of the measures above aimed at energy conservation and carbon reduction. The BAU scenario is a base situation without the policy interventions, while the POL scenario takes into consideration a series of policies and measures to reduce energy use and CO_2 emissions and includes five sub-scenarios which represent different sets of measures-the clean energy promotion (CEP), the industrial energy conservation (IEC), the energy conservation in buildings (BEC), the energy conservation in transports (TEC) and the renewable energy promotion (REP). Table 2 shows the assumptions and explanations about the two scenarios.

Table2

Assumptions and illustrations of the BAU and POL scenarios

Sector	BAU	POL		
	Assumption	Sub-scenario	Assumption	Measures illustration
Industry	It is constructed based on the current trends of parameters including energy efficiency and utilization patterns for different appliances and technologies in each sector, without considering further energy saving policies and measures in the future. However, the energy consumption and CO_2 emission in each sector grow along with the corresponding activity level, that is, the value added in the agriculture sector, the industrial sector, the construction sector and the commerce and service sector, the population in the household sector, and the turnover volume in the transport sector.	CEP	The natural gas will substitute for part of coal and oil (including diesel and fuel oil) and the substitution proportion will reach 70% and 50% by 2030.	Cut the end-use coal consumption and the natural gas development will enter a period with high speed.
		IEC	The efficiency of industrial energy use will improve by 30% in 2030.	Adjust the industrial energy structure; Reduce the energy use per unit value added, and strengthen the supervision of key energy-using units and promote energy-saving technologies.
Commerce and service		CEP	By 2030, the natural gas will replace 70% of coal.	
		BEC	The electricity and heat intensity will fall at the rates of 1.5% and 1% annually.	Improve the energy efficiency of household and office appliances. Promote the energy-saving behaviors.
Household		CEP	The natural gas will replace part of LPG and coal. By 2030, the substitution proportion of LPG will reach 70% in urban, and it will substitute 50% of LPG and coal in rural, respectively.	
		BEC	The electricity and heat intensity will fall at the rate of 1.5% and 1% annually.	
Transport		CEP	By 2030, passenger turnovers of LPG, CNG and electric buses will account for 5%, 35% and 10% of the total amount of buses; LPG and CNG taxis will undertake 10% and 20% of the total taxis' passenger turnovers; diesel and CNG cars will undertake 10% of the private passenger turnovers, respectively.	Increase the proportion of vehicles with clean energy.
		TEC	By 2030, the public passenger turnovers take up 60% of the total amount, with proportions of buses and metro accounting for 40% and 60%, respectively. The fuel efficiency of vehicles will increase by 30% in 2030.	Promote buses strongly; Accelerate the development of metro; Control the number of private vehicles; Improve fuel economy of vehicles; Promote the structure adjustment and energy conversion and carbon reduction of taxis. By 2020, the public passenger turnovers will cover 50% of the total amount in the center city.
Energy conversion		REP	By 2030, the electricity from renewable energy (including wind, hydro, solar) power plants will account for 15%, respectively.	Increase the construction of renewable energy power plants to optimize the energy supply structure.

3.4 Research framework

To begin with, this paper calculates Beijing's energy consumption and CO_2 emissions over 2005-2011 based on the Beijing energy balance table and the carbon-emission coefficient provided by IPCC. Under two scenarios, we estimate the future energy use and emission trends of end-use sectors and the energy conversion sector during 2012-2030 on the basis of LEAP-BJ. Meantime, measures and policies aimed at energy savings are also assessed. In the end, uncertainties are analyzed. The research framework is shown in Fig.2.

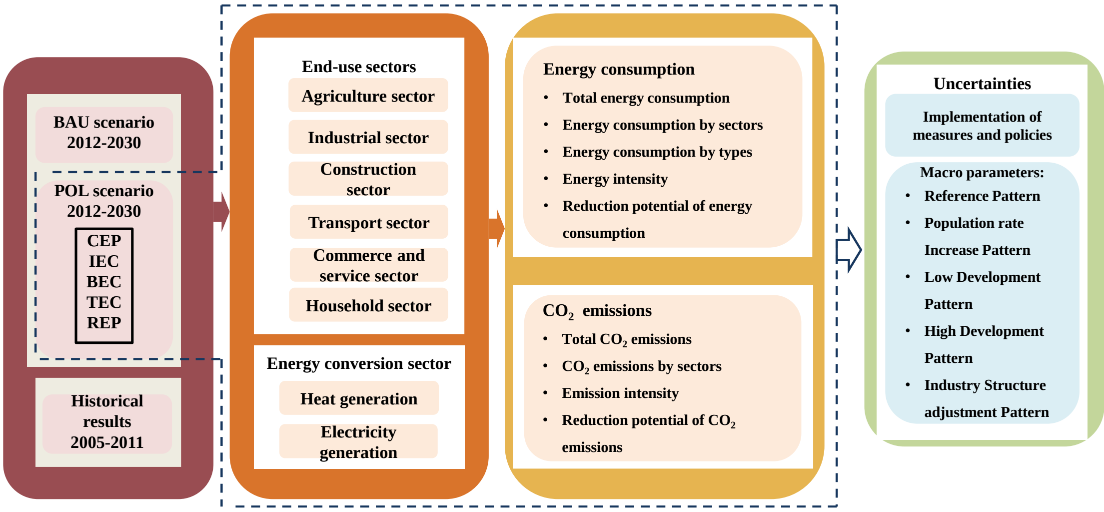


Fig.2

Research framework of this work

4 Results analysis and discussions

4.1 Historical energy consumption and CO_2 emissions

The total energy consumption increased from 55.21 million tce to 69.95 million tce at the average annual rate of 4.72% over 2005-2011, but in 2008 and 2011 it grew slowly (see Fig.3). Different from the total energy consumption which shows the upward trend, the total CO_2 emissions fluctuated obviously in 2008 and 2011. In 2008, Beijing hosted the Olympic Games, during which time the "even and odd-numbered license plates" limit[2] was implemented among the motor vehicles to make the traffic flow smooth and the air quality improved. In addition, the government invested a great deal of money on measures for energy savings and carbon reductions. Thus, the energy consumption almost did not rise and the CO_2 emission decreased in 2008. It also should be noted that because the coke consumption dropped more than 5 times in 2011 compared with that of 2010, the CO_2 emissions descended sharply in 2011.

[2] The "even and odd-numbered license plates" limit means that for one certain motor vehicle, it is only permitted to run on the driveway in every two days depending on whether the license plate number is even or odd. For example, on Monday, Wednesday and Friday, only motor vehicles with even license plate number can be used on the driveway and those with odd license plate number are permitted to be used on Tuesday and Thursday.

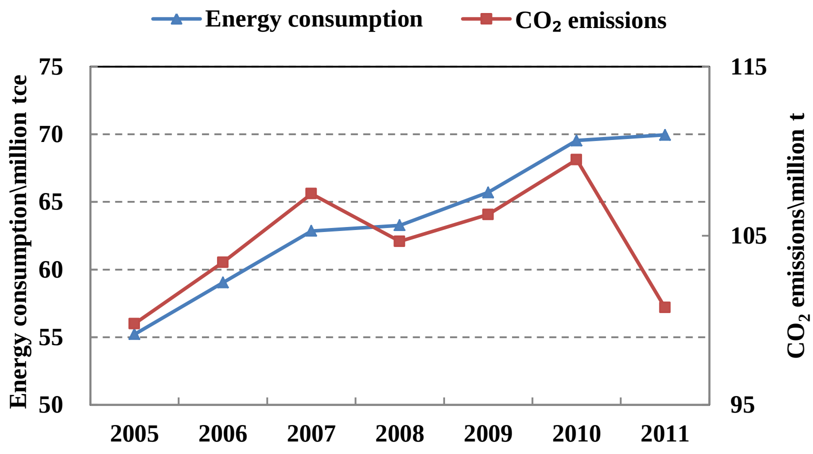
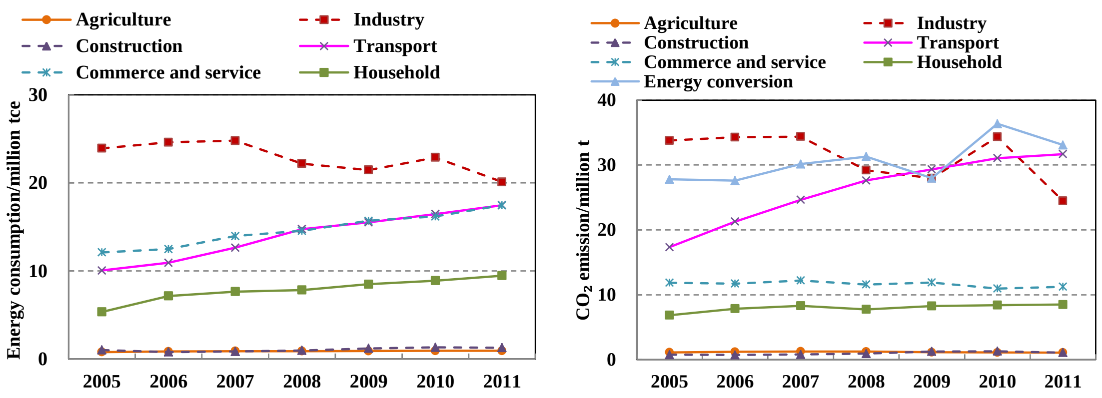


Fig.3

Total energy consumption and CO_2 emissions, 2005-2011

Among the six end-use sectors, the energy consumption in the industrial sector accounted for a large proportion (45%), followed by the commerce and service sector (23%) in 2005 (see Fig.4). Because the industry structure has been optimizing during the past years, the proportion of the industrial sector dropped to 30% in 2011, but the energy consumption in the commerce and service sector showed an upward trend. Although the commerce and service sector consumed more energy, its CO_2 emissions almost kept flat. That is why promoting the tertiary industry is important to achieve the goal of low carbon and energy conservation. The industrial sector was also the biggest CO_2 emitter in 2005. Its variation trend was almost the same with that of the total CO_2 emission, which dropped obviously in 2008 and 2001. The reasons for the changes are also the same with that of the total CO_2 emissions. The energy consumption and CO_2 emissions in the transport sector both have the escalating trend from 2005 to 2011, which derived, to a very great extent, from an increasing number of motor vehicles in Beijing during these years.



(a) Sectoral energy consumption (b) Sectoral CO_2 emissions

Fig.4

Sectoral energy consumption and CO_2 emissions, 2005-2011

Restricted by China's resource endowments of "*less gas and more coal*", at the very start, the coal dominated in the final energy consumption in Beijing, with accounting for 31% in 2005, as displayed in Fig.5. Along with Beijing's energy structure adjustment, the proportion of coal consumption slumped to 13% in 2011, lower than those of oil and electricity. In recent years, due to the rapid growth of motor vehicles and household appliances, the proportions of oil and electricity consumption have ascended, from 26% and 29% in 2005 to 33% and 36% in 2011, respectively. It also should be noticed that the natural gas consumption was witnessed an upward trend because of the low price and the improvement of economic development level. The level of economic development is one of the most important factors promoting the natural gas consumption. In Beijing, the natural gas was mainly used for household and commerce (public service). Therefore, at the stage of rational consumption of natural gas, it is natural that the natural gas will increase with the living standards improving and low natural gas price.

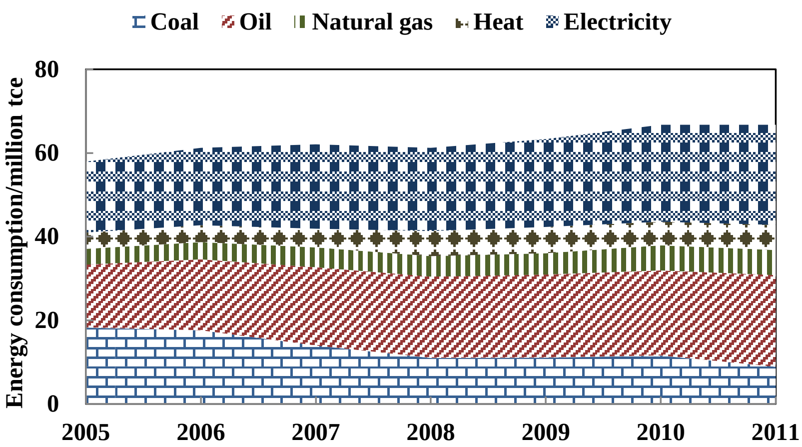


Fig.5

Energy consumptions of end-use sectors by fuel types, 2005-2011

Table 3

Energy intensity, CO_2 emissions intensity, Energy consumption and Emissions per capita, 2005-2011

	2005	2006	2007	2008	2009	2010	2011
Energy intensity (tce/10,000yuan)	0.79	0.73	0.64	0.57	0.54	0.49	0.43
Emissions intensity (t/10,000yuan)	1.43	1.27	1.09	0.94	0.87	0.78	0.62
Energy consumption per capita (tce/capita)	3.59	3.69	3.75	3.57	3.53	3.54	3.46
Emissions per capita (t/capita)	6.49	6.46	6.41	5.91	5.71	5.58	4.99

As illustrated in Table 3, from 2005 to 2011, the energy intensity in Beijing dropped significantly at an average annual rate of 10.67% and the emission intensity also decreased at a larger annual rate of 14.95%. The change of industry structure and the increasing efficiency of energy utilization were the two major factors impelling the energy intensity decrease and the latter one has a greater effect. Especially, the increasing efficiency of energy utilization in the industrial sector resulted in the drop of the whole energy intensity predominantly (Ye and Han 2008). The emissions and energy consumption per capita changed slightly, because the number of permanent residents also kept increasing during the past years.

4.2 Future total energy consumption and CO_2 emissions

Under both two scenarios, Beijing's total energy consumption shows an upward trend during 2012-2030, but the growth rates are significantly different (see Fig.6). The total energy consumption in six end-use sectors under the BAU scenario increases from 66.71 million tce in 2011 to 151.27 million tce in 2030, with an average annual growth rate of 4.40%. While under the POL scenario, with a series of energy-saving policies and measures, Beijing's total energy consumption raises at a slower growth rate of 2.71%. The cumulative amount of energy savings in POL scenario are projected to reach 351 million tce during the study years, 5.25 times of the total energy consumption in 2011. The total CO_2 emissions display the similar trends with the energy consumption.

The series of policies and measures to save energy and reduce emissions in the POL have the effect of controlling the growth of total energy consumption by 1.69% annually. However, it is still not realistic to reduce the energy consumption compared with the baseline year, since the economy continues to develop and the population tends to increase in the future, but the energy efficiency, energy structure and industry structure are not optimized sufficiently to match the economy and population growth. Therefore, the energy consumption and CO_2 emission tend to grow in the near future, but the energy-saving measures and policies are projected to suppress the growth to a great extent.

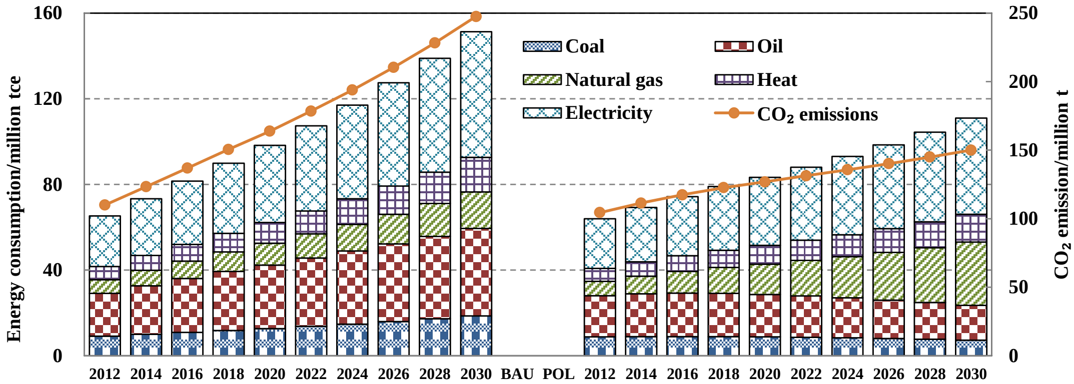


Fig.6

Total energy consumption by types and CO_2 emissions, 2012-2030

As shown in Fig.6, under the BAU scenario, the energy consumption structure changes slightly. But under the POL scenario, the proportion of coal consumption declines to 6.54% by 2030. In contrast, the proportion of natural gas consumption under the POL scenario grows rapidly, from 10.45% to 26.61% over 2012-2030, at an average annual growth rate of 1.86%. This result suggests a more optimized energy structure in the POL due to the measures of promoting the clean energy. The share of oil consumption also falls drastically, from 30.07% in 2011 to 14.63% in 2030, in which the TEC scenario contributes around 60% of the decrements. Therefore, improving the share of public passenger turnovers and the fuel efficiency of vehicles can benefit the oil consumption reduction greatly.

4.3 Energy intensity and CO_2 intensity

Under the two scenarios, the energy intensity remains the trend of declining, but at significantly different rates (see Table 4). In 2030, the energy intensities under the BAU scenario and POL scenario reach 0.29 tce/10,000 yuan and 0.21 tce/10,000 yuan, respectively. In the BAU scenario, the energy intensity decline may result from the improvement of overall social production efficiency. In terms of the POL scenario, in addition to the reasons above, a range of energy-saving-oriented policies and measures play a substantial role.

Table 4

Energy intensities under two scenarios, 2012-2030 (tce/10,000yuan)

	2012	2015	2020	2025	2030
BAU	0.37	0.35	0.33	0.31	0.29
POL	0.36	0.33	0.28	0.24	0.21

CO_2 emissions per capita still changes slightly under the BAU scenario, while under the POL scenario, it drops to 3.73 t/capita in 2030 from 4.99 t/capita in 2011, as shown in Fig.7. It indicates significant per-capita CO_2 emissions abatement effect from the measures, such as clean energy promotion, in the POL scenario. Compared with other developed cities, Beijing's CO_2 emissions per capita is higher than those of London, New York and Tokyo, while its per-capita energy consumption is lower than those of London and New York, slightly higher than that of Tokyo (Cai et al. 2013). Therefore, Beijing still needs to optimize the energy and industry structure. Furthermore, according to the data from World Bank (2010), Beijing's CO_2 emissions per capita is much higher than most of the European largest cities, such as Paris, Hamburg, Oslo, Stockholm, etc. and lower than most of the American largest cities, such as Boston, Chicago, Los Angeles, Seattle, Washington, DC, etc. On the one hand, European cities are much more compact, relying on public transportation greatly, which is a major reason for the dramatic differences in per-capita CO_2 emissions between newer cities in the US. On the other hand, the lower fuel cost in the US is another reason resulting in the higher CO_2 emissions per capita (World Bank, 2010).

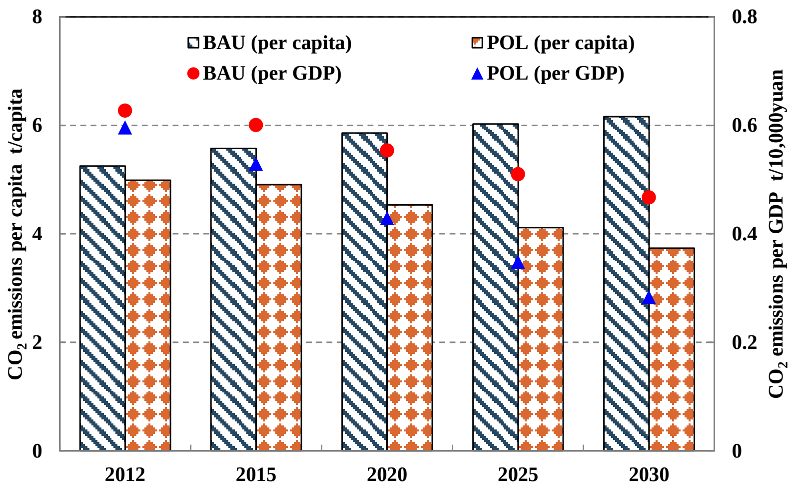


Fig.7

CO_2 emissions intensity and per-capita emissions under two scenarios, 2012-2030

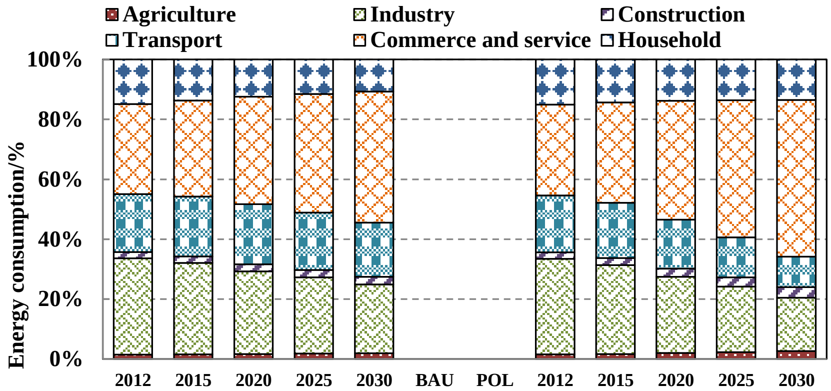
Regarding the emission intensity, under BAU it shows the downward trend from 0.63 t/10,000 yuan to 0.47 t/10,000 yuan over 2012-2030, at an average annual rate of 1.64%, which results from the same reason that causes the decline in energy intensity under the BAU scenario. The emission intensity decreases from 0.60 t/10,000 yuan in 2012 to 0.28t/10,000 yuan in 2030 under the POL scenario, with an average annual rate of 4.32%.

It can be noticed that under the POL scenario, the declines in emissions per capita and per GDP are greater than those of the BAU scenario. In addition, if policies and measures aimed at encouraging clean energy development and adjusting the energy structure are completely implemented, the decline rate of CO_2 emissions intensity (4.32%) is higher than that of the energy intensity (3.04%).

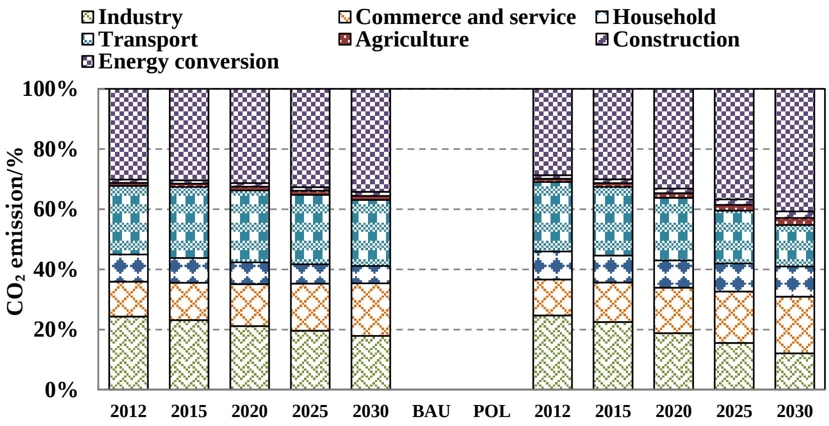
4.4 Sectoral energy consumption and CO_2 emissions

The proportion of energy consumption in commerce and service sector keeps increasing year by year (see Fig.8) in both scenarios and it will become the largest energy consumer among the six end-use sectors. The share of energy consumption in the transport sector tends to descend rapidly in the POL scenario from 18.97% in 2012 to 10.14% in 2030 because of the measures implemented to improve the share of public transport means and the fuel efficiency of vehicles. As the share of industrial sector's value added accounting for the GDP declines from 18.8% to 10.0% during 2011 and 2030, the proportion of industrial energy consumption is predicted to decrease in both scenarios. However, due to the improvement of energy efficiency in the industrial sector, the share slides more sharply under the POL scenario, with 17.84% in 2030.

In regard of the sectoral CO_2 emissions, the energy conversion sector maintains as the largest contributor in the both scenarios. Under the BAU scenario, both proportions of CO_2 emissions in the industrial sector and transport sector change to a small degree, while they decrease greatly under the POL scenario. For the commerce and service sector in the POL scenario, though its energy consumption rises sharply, its CO_2 emission still accounts for a small proportion (18.87%) in 2030.



(a) Sectoral energy consumption



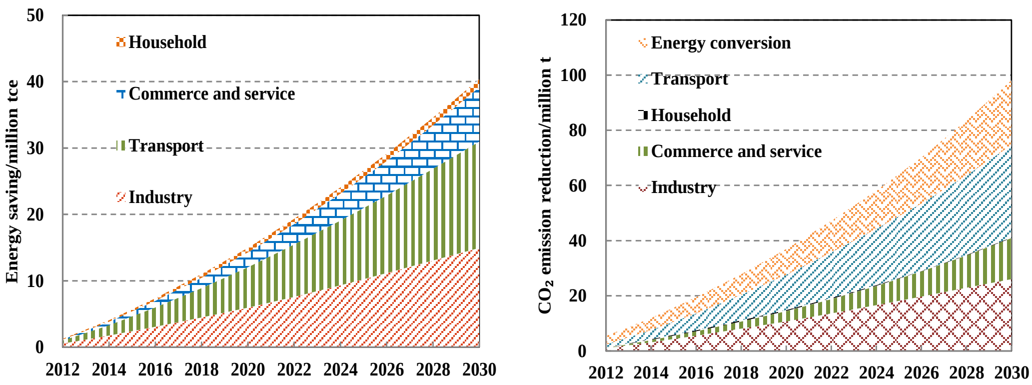
(b) Sectoral CO_2 emissions

Fig.8

Sectoral energy consumption and CO_2 emissions, 2012-2030

4.5 Reduction potential of different sectors and sub-scenarios

Under the POL scenario, both the energy savings and CO_2 emissions reduction gradually increase, but the abatement potentials of various sectors are different, as shown in Fig.9. From 2012 to 2030, energy savings in the transport sector account for the largest proportion among the five sectors, followed by the industrial sector. The energy-saving rate in the commerce and service sector steadily climbs to 20.26% by 2030. Similarly, the carbon reduction in the industrial sector and the transport sector also dominate the total amount. Besides, the energy conversion sector also has an important contribution to the carbon reduction, with the share of 24.00% in 2030. Therefore, the transport sector and industrial sector are promising to be the key energy conservation and carbon reduction sectors in the future. Furthermore, it is necessary to use more renewable and clean energy resources in the energy conversion sector to realize the goal of CO_2 emissions reduction.



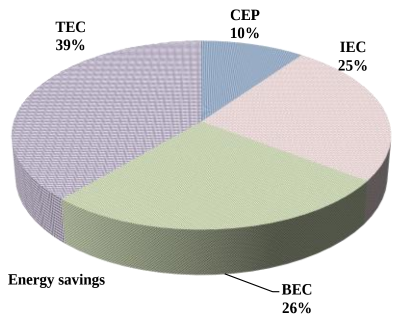
(a) Energy savings by sectors

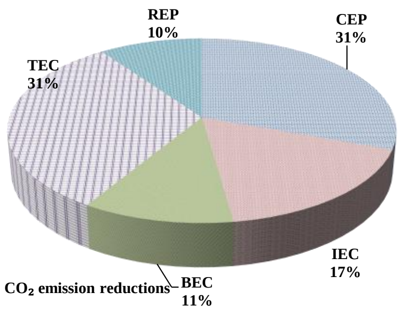
(b) CO_2 emissions reduction by sectors

Fig.9

Energy savings and CO_2 emissions reduction by sectors under the POL scenario, 2012-2030

Among the five sub-scenarios in the POL scenario, the greatest contribution of energy savings and CO_2 emissions reduction is from the TEC, with the contribution rates of 39% and 31%, respectively, shown as in Fig.10. It indicates that energy-saving measures in the TEC have the largest mitigation potential for energy consumption and CO_2 emissions. Though the CEP only contributes 10% of energy savings, it can reduce 31% of the CO_2 emissions, the same with that of the TEC, because the measures and policies in the CEP cover the industrial, commerce and service, household and transport sectors. The BEC and IEC sub-scenarios mainly focus on energy efficiency improvement in the household, commerce and service and industrial sector and have narrow contribution in CO_2 emission reductions, especially the BEC. By deploying the renewable energy resources in the energy conversion sector, the REP contributes 10% of the CO_2 emissions reduction.





(b) Energy savings of sub-scenarios (b) CO_2 emissions reduction of sub-scenarios

Fig.10

Energy savings and CO_2 emissions reduction of sub-scenarios in the POL scenario, 2012-2030

4.6 Uncertainty analysis of policies implementation and macro parameters

The implementation of measures and policies has some uncertainties. For the industrial sector, the clean energy promotion is difficult because of the constraints of infrastructure construction and the cost. In terms of the transport sector, the target of controlling the private cars and promoting public transport tend to be achieved easily. Because some measures and policies have been implemented to control the number of private cars, e.g. the Yaohao policy (every month, the government selects a limited number randomly from the applicants of automobile license to get the license). Meanwhile, due to the severe weather of fog and haze in recent two years, residents start to decrease the use of private. However, the increase of vehicles with clean energy has some uncertainties, since the CNG buses, taxis and cars are unpopular in Beijing now. In all, the main uncertainties in the implementation of measures and policies lie in the industrial sector and the transport sector.

On the other hand, the macro parameters of the society and economy also have some uncertainties in this model. In order to identify the uncertainties of macro variables, it is necessary to examine responses of the POL scenarios to the key input parameters. The main driver factors of energy consumption and CO_2 emissions are population and economic development. In this study, we employ three variables, including population growth, GDP growth rate and industrial structure[3]

[3] The industrial structure adjustment also belongs to the uncertainty of the implementation of measures and policies.

to complete the sensitivity analysis. Five development patterns are designed, illustrated in Table 5.

Table 5

Explanations of different development patterns

Development patterns	Explanations
Reference Pattern (RP)	The POL scenario
Population rate Increase Pattern (PIP)	The population growth rate increases by 20% than the Reference Pattern, set as 4.428%
Low Development Pattern (LDP)	The growth rate of GDP decreases by 20% than the Reference Pattern
High Development Pattern (HDP)	The growth rate of GDP increases by 20% than the Reference Pattern
Industry Structure adjustment Pattern (ISP)	The share of value added of the commerce and service sector accounts for 90% with the industrial sector 4% by 2030

Under the above five development patterns, the energy consumption and CO_2 emissions change are as shown in Fig.11.

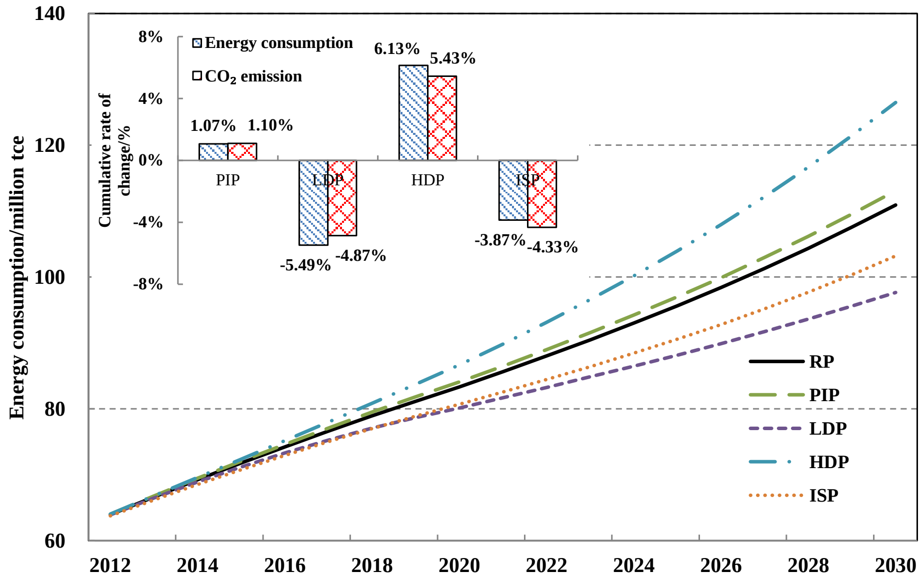


Fig.11

Sensitivity analysis of energy consumption and CO_2 emissions in the POL scenario

The results point that the three variables have great influence on Beijing's energy consumption and CO_2 emissions, of which the economic development rate is the largest.

The cumulative energy savings and carbon reductions under the HDP run up to 6.13% and 5.43% of the cumulative total amounts of RP during 2012-2030, respectively. The elasticity coefficients are 0.307 and 0.272, respectively, which means that under the POL scenario, 1% increase in Beijing's GDP growth rate is associated with 3.07 ‰ of the cumulative total energy consumption as well as 2.72 ‰ of CO_2 emissions.

The impact of industrial structure adjustment on CO_2 emissions (-4.33%) is much larger than that on energy consumption (-3.87%), indicating that a series of measures such as upgrading the industrial structure and changing the economic development mode play a critical role in CO_2 emissions reduction (Mi et al. 2014). Now Beijing is in the process of economic transition and the tertiary industry is encouraged to develop strongly. In the Beijing's 12th Five-Year Plan, the service sector is expected to account for at least 78% of the GDP by 2015. This will benefit for the energy conservation, especially for the carbon reduction.

Population growth rate does not have much effect on energy consumption and CO_2 emissions. Under the PIP, the cumulative total energy savings and emission reductions over 2012-2030 are less than 1% of the total amount of RP.

5 Conclusions and policy implications

In this work, energy consumption and CO_2 emissions of Beijing are calculated first during 2005-2011. Based on a series of energy conservation planning program issued in Beijing, the LEAP-BJ model is developed to study the energy consumption and CO_2 emissions of Beijing's six end-use sectors and the energy conversion sector over 2012-2030 under the BAU scenario and POL scenario. On the one hand, we predict Beijing's future trend of energy use and CO_2 emissions. On the other hand, we also evaluate and analyze the effectiveness of energy saving policies. Further uncertainties are analyzed, including the implementation of measures and policies, and the main driving factors, e.g. demographic and economic development. Some conclusions are drawn as follows:

(1) During 2005-2011, the energy consumption kept increasing, while the total CO_2 emissions fluctuated obviously in 2008 and 2011. Since energy and industry structures have been optimized to a certain extent, the proportions of energy consumption and CO_2 emissions in the industrial sector dropped greatly. Furthermore, the coal consumption also decreased sharply, with oil, electricity and natural gas consumptions increasing. During 2005-2011, the energy intensity and CO_2 emissions intensity maintained descending. In all, the situation of Beijing's energy consumption and CO_2 emissions in the past few years is in the process of optimization.

(2) From the results of the LEAP model, if the policies are completely implemented, the POL scenario is projected to reduce 21.36% and 35.37% of the total energy consumption and CO_2 emissions than the BAU scenario during 2012 and 2030. But it is still not possible to reduce the energy consumption compared with the baseline year, with increasing 84.56 and 44.22 million tce for BAU and POL in 2030, respectively. The POL scenario presents a more optimized energy structure compared with the BAU scenario, with the decrease of coal consumption and the increase of natural gas consumption. Owing to measures in the transport sector, the oil consumption in the POL also declines sharply. Accordingly, the declines of energy intensity and CO_2 intensity in the POL scenario are greater than those of the BAU scenario.

(3) The commerce and service sector will become the largest energy consumer among the six

end-use sectors, but its CO_2 emission still accounts for a small proportion in the future. The energy conversion sector maintains as the largest contributor in the both scenarios in regards of CO_2 emissions. The transport sector and the industrial sector are the two most potential sectors in energy savings and carbon reduction. In terms of sub-scenarios, the TEC is the most effective sub-scenario in energy savings and CO_2 emissions mitigation. In the meantime, the CEP is also the most effective to reduce CO_2 emissions. Because of deploying the renewable energy resources in the energy conversion sector, the REP also contributes part of the CO_2 emissions abatement.

(4) Population, economic development and industrial structure have great influence on Beijing's energy consumption and CO_2 emissions, of which the rate of economic development is the largest. With 1% increase in Beijing’s GDP growth rate, the cumulative total energy consumption and CO_2 emissions during 2012-2030 will increase by 3.07 ‰ and 2.72 ‰. The impact of industrial structure adjustment on CO_2 emissions is considerable, indicating that a series of measures such as upgrading the industrial structure and changing the economic development mode play a critical role in CO_2 emissions reduction. But it does not benefit greatly the energy conservation compared with the CO_2 emissions reduction.

Based on the conclusions above, the following policy implications for energy conservation and low carbon in Beijing are put forward.

(1) Measures and policies in the transport sector (TEC sub-scenario) are the most effective in terms of energy savings and CO_2 emissions reduction, accordingly, the transport sector has the most reduction potential. Therefore, on the one hand, the public transport system including the metros and bus system should be improved to encourage more residents to take public transportation; on the other hand, the private vehicles should be controlled continuously and the vehicles with clean energy and fuel-saving standards should be popularized. However, it might be difficult to implement the alternative energy measures since the CNG buses, taxis and cars are unpopular in Beijing now, so the policies are necessary to boost the industry of new energy automotive.

(2) The energy structure optimization (CEP sub-scenario) has the greatest potential as well as the TEC sub-scenario in regards of carbon reduction, so it is highly recommended to promote clean energy, such as natural gas, to replace high-carbon energy resources. However, according to the results, if the policies and measures are implemented completely, the natural gas consumption will reach 29.51 million tce in 2030, 4.93 times of that in 2011. Considering the limit of natural resources in Beijing, this is totally a huge challenge for the energy supply system. Thus to make the policies function well and the energy structure optimize successfully, the government should ensure the energy supply system, especially the natural gas supply.

(3) The IEC and BEC sub-scenarios do not save as much energy as the TEC. Therefore, in the industrial sector, the energy efficiency improvement should cooperate with the clean energy promotion, but considering the constraints of infrastructure construction and the cost, the government should issue proper incentive policies to promote the natural gas use. Regarding

the results of BEC sub-scenario, the awareness and behaviors for energy conservation of residents is also an indispensable part. Thus, it is necessary to make the public realize the significance and necessity, which requires the relevant departments to guide and promote.

In this study, we only consider the effectiveness of different energy-saving measures, but we also should take the cost of measures into consideration to provide more insightful results for decision-makers in the future.

Reference：

Arnold, M., & Barth, V. (2012). Open innovation in urban energy systems. *Energy Efficiency*, 5(3), 351-364.

Beijing Statistical Bureau (2006-2012). Beijing Statistical Yearbook (2006-2012). Beijing: China Statistics Press. (In Chinese).

Bi, J., Zhang, R., Wang, H., Liu, M., & Wu, Y. (2011). The benchmarks of carbon emissions and policy implications for China' cities: Case of Nanjing. *Energy Policy*, 39(2011), 4785-4794.

Bohringer, C., & Rutherford, T.F. (2009). Integrated assessment of energy policies: decomposing top-down and bottom-up. *Journal of Economic Dynamics and Control,* 33, 1648-1661.

Cai, W.J., Wang, C., Chen, J.N., Wang, K., Zhang, Y., & Li, X.D. (2008). Comparison of CO_2 emission scenarios and mitigation opportunities in China's five sectors in 2020. *Energy Policy*, 36(2008), 1181-1194.

Cai, Z., Ou, X., Zhang, X., Zhang, X., He, J., & Xing, Y. (2013). Comparative study of energy consumption and CO_2 emissions between Beijing and London. *Frontiers in Energy*, 7(1), 1-5.

de la Rue de Can, S., & Price, L. (2008). Sectoral trends in global energy use and greenhouse gas emissions. *Energy Policy*, 36(2008), 1386-1403.

Dhakal, S. (2003). Implications of transportation policies on energy and environment in Kathmandu Valley, Nepal. *Energy Policy*, 31(2003), 1493-1507.

Dhakal, S. (2009). Urban energy use and carbon emissions from cities in China and policy implications. *Energy Policy*, 37 (2009), 4208-4219.

Fan, J.-L., Liao, H., Liang, Q.-M., Tatano, H., Liu, C.-F., & Wei, Y.-M. (2013). Residential carbon emission evolutions in urban-rural divided China: An end-use and behavior analysis. *Applied Energy*, 101(2013), 323-232.

Feng, Y.Y., & Zhang, L.X. (2012). Scenario analysis of urban energy saving and carbon abatement policies: A case study of Beijing city, China. *Procedia Environmental Sciences*, 13(2012), 632-644.

Feng, Y.Y., Chen, S.Q., & Zhang, L.X. (2013). System dynamics modeling for urban energy consumption and CO_2 emissions: A case study of Beijing, China. *Ecological Modelling*, 252(2013), 44-52.

Gomi, K., Shimada, K., & Matsuoka, Y. (2010). A low-carbon scenario creation method for a local-scale economy and its application in Kyoto city. *Energy Policy*, 38(2010), 4783-4796.

Huang, C., Chen, C.H., Wang, B.Y., Dai, Y., Zhao, J., & Wang, H.K. (2005). Urban travel modal split and its impact on energy and environment. *Journal of Highway and Transportation Research and Development*, 22(11), 163-166. (In Chinese)

IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume II: Energy. Institute for Global Environmental Strategies, Japan.

IPCC (2007). IPCC Fourth Assessment Report (AR4). London: Cambridge University Press.

Li, L., Chen, C., Xie, S., Huang, C., Cheng, Z., Wang, H., et al. (2010). Energy demand and carbon emissions under different development scenarios for Shanghai, China. *Energy Policy*, 38(2010), 4797-4807.

Limmeechokchaia, B., & Chawana, S. (2007). Sustainable energy development strategies in the rural Thailand: the case of the improved cooking stove and the small biogas digester. *Renewable Sustainable Energy Review*, 11(5), 818-837.

Lin, J., Cao, B., Cui, S., Wang, W., & Bai, X. (2010). Evaluating the effectiveness of urban energy conservation and GHG mitigation measures: The case of Xiamen city, China. *Energy Policy*, 38(2010), 5123-5132.

Mi, Z.-F., Pan, S.-Y., Yu, H., & Wei, Y.-M. (2014). Potential impacts of industrial structure on energy consumption and CO_2 emission: a case study of Beijing. *Journal of Cleaner Production*, in press.

National Bureau of Statistics P.R. China (2012). China energy statistical yearbook (2012). Beijing: China Statistics Press. (In Chinese).

Olivier, J.G.J., Janssens-Maenhout, G., Muntean, M., & Peters, J.A.H.W. (2013). (PBL) Trends in Global CO_2 Emissions. PBL Netherlands Environmental Assessment Agency, Hague, Netherlands. ISBN: 978-94-91506-51-2.

Parshall, L., Gurney, K., Hammer, S.A., Mendoza, D., Zhou, Y., & Geethakumar, S. (2010). Modeling energy consumption and CO_2 emissions at the urban scale: Methodological challenges and insights from the United States. *Energy Policy*, 38(2010), 4765-4782.

Phdungsilp, A. (2010). Integrated energy and carbon modeling with a decision support system: Policy scenarios for low-carbon city development in Bangkok. *Energy Policy*, 38(2010), 4808-4817.

Pradhan, S., Ale, B.B., & Amatya, V.B. (2006). Mitigation potential of greenhouse gas emission and implications on fuel consumption due to clean energy vehicles as public passenger transport in Kathmandu Valley of Nepal: a case study of trolley buses in Ring Road. *Energy*, 31(12), 1748-1760.

Roger, P.J., Wigley, T., & Green, C. (2008). Dangerous assumptions. *Nature*, 452, 531-532.

Rutter, P., & Keirstead, J. (2012). A brief history and the possible future of urban energy systems. *Energy Policy*, 50(2012), 72-80.

Shin, H.-C., Parka, J.-W., Kim, H.-S., & Shin, E.-S. (2005). Environmental and economic assessment of landfill gas electricity generation in Korea using LEAP model. *Energy Policy*, 33(2005), 1261-1270.

Solomon, S., Plattner, G.-K., Knutti, R., & Friedlingstein, P. (2009). Irreversible climate change due to carbon dioxide emissions. *PNAS*, 106, 1704-1709.

Steemers, K. (2003). Energy and the city: density, buildings and transport. *Energy and Buildings*, 35(2003), 3-14.

Stockholm Environment Institute (SEI) (2011). User Guide, LEAP: Long Range Energy Alternative Planning System. Stockholm Environment Institute, Boston.

Wang, K., Wang, C., Lv, X., & Chen, J. (2006). Abatement potential of CO_2 emissions from China's iron and steel industry based on LEAP. *Journal of Tsinghua University (Science and Technology)*, 46(12), 1982-1986. (In Chinese)

Wang, Q.Y. (2006). The energy conservation handbook 2006. Energy Conservation and Environmental Protection Magazine, Beijing. (In Chinese)

Wang, Z., Yin, F., Zhang, Y., & Zhang, X. (2012). An empirical research on the influencing factors of regional CO_2 emissions: Evidence from Beijing city, China. *Applied Energy*, 100(2012), 277-284.

World Bank (2010). Cities and climate change: an urgent agenda. Washington DC.

Xi, F., Geng, Y., Chen, X., Zhang, Y., Wang, X., Xue, B., et al. (2011). Contributing to local policy making on GHG emission reduction through inventorying and attribution: A case study of Shenyang, China. *Energy Policy*, 39(2011), 5999-6010.

Ye, Y.-L., & Han Y.-D. (2010). Effect of industrial development on energy intensity in Beijing. Journal of North China Electric Power University (Social Sciences), (3), 16-20. (In Chinese)

Yu, H., Yang, R., Zhang, Y., & Wang, S. (2013). Study on the energy demand and environmental emissions of urban transport-A case study of Beijing. *Journal of Beijing Institute of Technology (Social Sciences edition)*, 15(5), 10-15. (In Chinese)

Zhang, X.P. (2005). Temporal-spatial characteristics of energy consumption in China and its determinants since the 1990s. *China Population, Resources and Environment*, 15, 38-41. (In Chinese)

Zhang, J., Zhang, Y., Yang, Z., Fath, B. D., & Li, S. (2013). Estimation of energy-related carbon emissions in Beijing and factor decomposition analysis. *Ecological Modelling*, 252(2013), 258-265.

Zhang, Q.Y., Tian, W.L., Wei, Y.M., & Chen, Y.X. (2007). External costs from electricity generation of China up to 2030 in energy and abatement scenarios. *Energy Policy*, 35(2007), 4295- 4304.

Zhou, D.，Levine, M., Dai, Y., Yu, C., Guo, Y., Sinton, J.E., et al. (2004). China's sustainable energy future: Scenarios of energy and carbon emissions (summary). Lawrence Berkeley National Laboratory. Paper LBNL-54067. < http://repositories.cdlib.org/lbnl/LBNL-54067> .

Zhou, J., Cui, S.H., Lin, J.Y., & Li, F. (2011). LEAP based analysis of transport energy consumption and air pollutants emission in Xiamen city. *Environmental Science and Technology*, 34(11), 164-170. (In Chinese)