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# Measurement and Scenario Simulation of Effect of Urbanisation on Regional $CO_2$ Emissions Based on UEC-SD Model: A Case Study in Liaoning Province, China

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**Abstract:** Based on the logical causal relationship and taking Liaoning Province, China, which is the Chinese traditional industrial base and is in the stage of accelerated urbanisation, as a case study, this study builds the 'Urbanisation-Energy Consumption-$CO_2$ Emissions System Dynamics (UEC-SD)' model using a system dynamics method. The UEC-SD model is applied to analyse the effect of the urbanisation process on the regional energy structure and $CO_2$ emissions, followed by simulation of future production and living energy consumption structure as well as the evolutionary trend of $CO_2$ emissions of three urbanisation scenarios (low speed, intermediate speed and high speed) under the assumed boundary conditions in urban and rural areas of Liaoning Province, China. The results show that the urbanisation process can alter production and the living energy consumption structure and thereby change regional $CO_2$ emissions. An increase in the urbanisation rate in case area will lead to regional $CO_2$ emissions rising in the short term, but when the urbanisation rate approaches 80%, $CO_2$ emissions will reach a peak value and then decrease. Comparison of different urbanisation rates showed that production and living energy consumption exhibit different directions of change and rules in urban and rural areas. The effect of urbanisation on $CO_2$ emissions and energy structure is not direct, and urbanisation can increase the differences in energy and $CO_2$ emissions between urban and rural areas caused by the industrial structure, technical level and other factors.

**Keywords:** urbanisation; $CO_2$ emissions; scenario simulation; Urbanisation-Energy Consumption-$CO_2$ Emissions System Dynamics (UEC-SD) model; Liaoning Province; China

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## 1 Introduction

Urbanisation is an important process and represents an inevitable stage in economic and social development. This process has a great, far-reaching impact on changes in the regional economy, society and ecological environment. (You *et al.*, 2005; Fang and Wang, 2013; Xie and Wang, 2013). A great deal of research shows that urbanisation can affect the regional energy structure and $CO_2$ emissions by changing the spatial distribution of the population, the regional industrial structure, and human production and living modes (Ghosh and Kanjilal, 2013). In developing countries, with the rapid development of urbanisation, this process has become one of the key factors that must be considered in research on changes in the regional energy structure and trends of $CO_2$ emissions as well as in policies aimed at the reduction of $CO_2$ emissions (Hossain, 2011). Great

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importance has been attached to this process by scholars in the energy policy field. Further exploration of the mechanisms underlying the effect of urbanisation on regional $CO_2$ emissions and accurately calculating the quantitative relationship between urbanisation and $CO_2$ emissions have become hot topics in academic research (Poumanyvong and Kaneko, 2012).

Some scholars have verified the logical relationship between urbanisation and $CO_2$ emissions through theories or models (Zhang and Lin, 2012). For example, Martinez-Zarzoso and Maruotti (2011) used a semi-parametric mixed model to test and verify the effect of urbanisation on $CO_2$ emissions, but the directions of this effect are different in different countries. Some scholars have tested and calculated the quantitative relationships between urbanisation and $CO_2$ emissions through models (Sadorsky, 2014). For example, Zhang and Tian (2012) studied the effect of urbanisation on the carbon balance of the terrestrial ecosystem and found that the land-use change due to urbanisation caused the southern region in America to release 0.21 Pg C from 1945 to 2007. However, it should be noted that in many existing researches, the relationship between urbanisation and $CO_2$ emissions is tested and estimated by using the methods of multiple regression analysis and unit root testing, and only in few researches, the relationship is calculated and simulated based on causality after the mechanism analysis of the effect of urbanisation on $CO_2$ emissions (Li *et al*., 2012a). Therefore, many researches can verify and reveal the quantitative correspondence, but it is difficult to accurately simulate the true extent of the future impact of urbanisation on (increasing or reducing) regional $CO_2$ emissions. At the same time, urbanisation and $CO_2$ emissions are both dynamic processes, and under conditions of dynamic evolution, both quantitative relationships and even the direction of the effect may change (Poumanyvong and Kaneko, 2010). In the existing researches, the system analysis combined with industry trends, energy technology level change and household energy consumption structure change is few, and then it is also difficult to simulate and determine accurately the direction and extent of the effect of the evolution of future regional urbanisation on $CO_2$ emissions to provide an accurate scientific basis for developing policies aimed at the reduction of $CO_2$ emissions with a high efficiency and low cost, improving urbanisation schemes and other practical policy work.

Hence, breaking through the research perspective of correlation, basing on causality and utilising a system dynamics model combined with an actual case study, the present study quantitatively analyses and simulates the long-term dynamic process and extent of urbanisation effects on regional energy consumption and $CO_2$ emissions, according to causality that the urbanisation can change the urban and rural population distribution, as well as the regional production and living energy consumption structure.

Liaoning Province is located along the eastern coast of China, and then China is the largest developing country in the world and produces the most $CO_2$ emissions. Liaoning Province is characterised by high resource consumption and $CO_2$ emissions and is in a key stage of urbanisation acceleration and rapid economic growth. The region is facing the dual pressures of greatly reducing $CO_2$ emissions and meeting the urgent requirements of economic and social development. Therefore, Liaoning Province is one of the most representative provinces showing one of the most outstanding contradictions regarding $CO_2$ emissions and regional development in China. Empirical research on this study area has practical significance and provides an important reference values for coordinating the relationship between urbanisation and $CO_2$ emissions, contributing to the development of policies aimed at the reduction of $CO_2$ emissions and generating urbanisation patterns with high a efficiency and reasonability and relieving the contraction of the regional development demand in areas exhibiting rapid urbanisation, high energy consumption and high $CO_2$ emissions.

## 2 Study Area

Liaoning Province (38°43′–43°26′N, 118°53′–125°46′E), located in Northeast China, is in a temperature zone corresponding to a continental monsoon climate. The annual solar radiation is between $1 \times 10^{12}$ and $2 \times 10^{12}$ cal/km$^2$, and the average annual sunshine is between 2100 h and 2600 h. The average annual temperature is between 7℃ and 11℃. The average annual frost-free period is between 130 d and 200 d, which increases gradually from the northwest to the southeast. The average annual rainfall is between 600 m and 1100 mm. The total land area is 145 900 km$^2$, accounting for 1.5% of the total land area of China. The total population at the end of 2009 was $4.256 \times 10^9$, accounting for 3.19% of the total Chinese population.

### 2.1 Accelerating development of urbanisation process

In recent years, the urbanisation process in Liaoning Province has accelerated, especially since 2005. The urbanisation rate has maintained an average annual growth rate of 1.61%, and an average annual growth rate of more than 2% has been observed in the last 3 years. In 2012, the urbanisation rate in Liaoning Province reached 65.63% (Fig. 1).

### 2.2 Gradual increases of $CO_2$ emissions

Liaoning Province is the typical old Chinese industrial base, and its industrial structure is biased toward heavy industry (Zhang, 2008). The continuously accelerating urbanisation process promotes regional economic development and urban construction, resulting in increased consumption of fossil fuel energy and a continuous rise in $CO_2$ emissions. From 1985 to 2012, $CO_2$ emissions increased continuously from $4.43 \times 10^7$ t to $1.67 \times 10^8$ t, showing an annual average growth rate of 5.63%, especially after 2005, when the accelerated development of economy led the annual average growth rate of $CO_2$ emissions to reach 9.58% (Fig. 2).

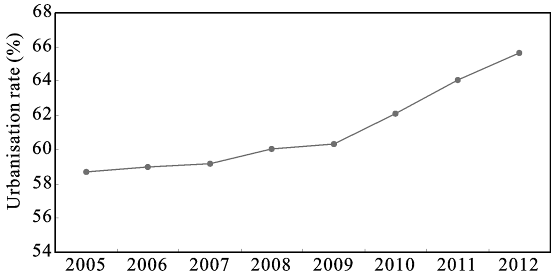

**Fig. 1** Growth of urbanisation rate in Liaoning Province in recent years

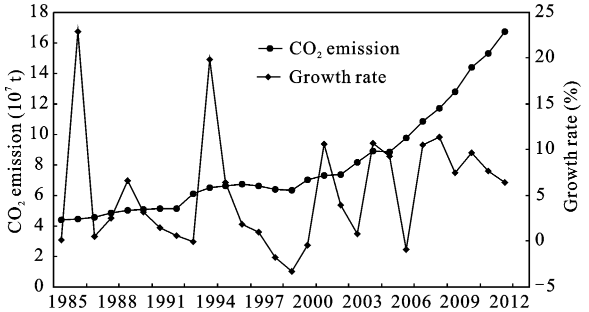

**Fig. 2** Quantity and growth rate of $CO_2$ emissions of Liaoning Province in recent years

On the Copenhagen Meeting in 2009, the Chinese Government promised that by 2020, the $CO_2$ emissions per GDP would be reduced by 40%–45% of 2005 level. As a traditional industrial area, Liaoning Province generates high $CO_2$ emissions. Therefore, Liaoning Province bears heavy pressure to reduce $CO_2$ emissions according to the targeted $CO_2$ emissions reduction for China. On the other hand, this area also faces the accelerating development of urbanisation and the urgent demand of maintaining sustained economic growth. Particularly since 2013 Chinese Government has stressed maintaining the advancement of urbanisation as an important engine of economic growth, which means that the further development of urbanisation may result in larger and more far-reaching impacts on the economy, society and ecological environment as well as on the reduction of $CO_2$ emissions in the future in Liaoning Province. Therefore, further studies on the effect of urbanisation on regional $CO_2$ emissions and coordinating relationship between urbanisation and policies for the reduction of $CO_2$ emissions have significant and practical meaning for the future development of the case study area, in addition to presenting important reference value for empirical research and decision making in many other countries and regions.

## 3 Causal Logic Relationship Between Urbanisation Process and Regional $CO_2$ Emissions

### 3.1 Differences in fossil fuel energy consumption structure of production in urban and rural areas

The industrial structure is different between urban and rural areas. The industrial structure of urban areas mainly involves industry and the service industry, while the industrial structure of rural areas mainly involves agriculture. The energy consumption per unit of added value is different in different industries. Therefore, the energy consumption structure and energy consumption associated with production in urban and rural areas show great differences. For example, in Liaoning Province, there are a large number of resource-based cities, and the rise of urban and industrial agglomeration is based on the exploitation of iron, steel, coal and other mineral resources. Therefore, the industrial type of urban areas mainly involves industries exploiting metal and non-metal resources, including coal, steel and oil, the equipment manufacturing industry, the chemical industry, the transportation industry and so on. In addition, it is worth noting that many industrial and service activities in rural areas, such as the processing of agricultural products, the mining of metallic and non-metallic resources and transportation, are mainly conducted by the surplus agricultural labour force. When studying the differences in energy consumption between urban and rural areas, these rural non-agricultural industries belong to rural energy systems, however, when studying the differences in energy consumption structures between urban and rural areas, they belong to urban energy systems. The energy consumption per unit of added value by these rural non-agricultural industries is lower than that by urban industries. In 2011, the proportions of primary energy consumption for oil, natural gas and coal by urban industries and rural non-agricultural industries were 49.98%, 45.49% and 4.53%, respectively (Fig. 3). The electric power supply in Liaoning Province comes from thermal power generation, and electrical power consumption is therefore converted into standard coal according to the thermal power generation efficiency after removing hydropower.

The industrial structure of rural areas mainly involves farming, forestry, animal husbandry and fishery. The energy consumption in rural areas is lower than that in urban areas, while the energy consumption structure in rural areas is different from that in urban areas. The specific proportions corresponding to oil, natural gas and coal are 69.15%, 3.6% and 27.25% respectively (Fig. 3).

### 3.2 Differences in fossil fuel energy consumption structure relevant to living in urban and rural areas

The differences in the living modes in urban and rural areas mean that energy consumption and energy consumption structure associated with living in these areas are also different. This principle is same as that underlying the difference in production energy consumption. The energy consumption associated with urban living is mainly in the form of electricity, oil, gas, liquefied petroleum gas, coal, and natural gas. The proportions of primary energy consumption corresponding to oil, natural gas and coal converted by these types of energy are 54.71%, 2.98% and 42.31%, respectively. In contrast, the proportion of natural gas consumed in rural living is low, and energy consumption in rural living is mainly in the form of firewood, coal, electricity, gasoline, and diesel fuel. The proportions of primary energy consumption

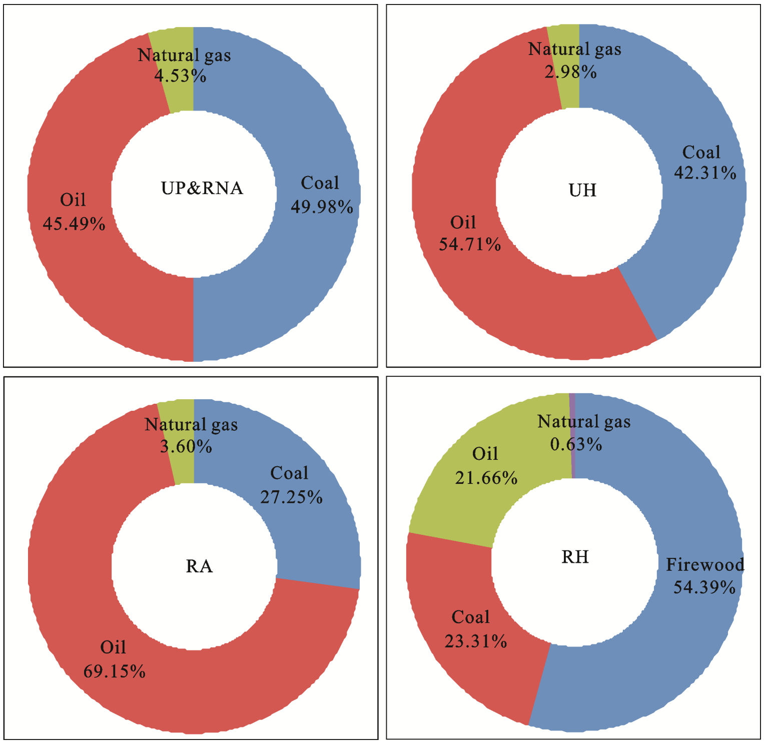

**Fig. 3** Differences in energy consumption structure relevant to production and living in urban and rural areas in Liaoning Province in 2011. UP means urban production; RNA means rural non-agricultural industries; UH means urban households; RA means rural agricultural industries; RH means rural household

corresponding to oil, natural gas, coal and firewood converted by these types of energy are 21.66%, 0.63%, 23.31% and 54.39%, respectively (Fig. 3). The electricity used in both urban and rural living comes from the unified electrify power grid of Liaoning Province, and the coal consumed in electricity power generation has been calculated in urban production. Therefore, the electrical energy consumption of household living is not converted to coal.

### 3.3 Cause and process about effect of urbanisation on regional carbon emissions change

According to the above-mentioned analysis, during urbanisation, the population migrates from rural areas to urban areas, and then the rural mode of production and living change to the urban mode. However, due to the differences in the energy consumption structures related to production and living in urban and rural areas, the structure and quantity of energy consumption will change. According to the population base in Liaoning Province in 2012, when the urbanisation rate increases by 1%, nearly 440 000 people will experience a shift from a rural energy consumption structure to an urban structure. Therefore, urbanisation has a large effect on regional energy consumption. Thus, by changing the regional energy consumption structure and total energy consumption, the urbanisation process can change the regional $CO_2$ emission pattern. This is the effect of urbanisation on $CO_2$ emissions.

In addition, the urbanisation process may not only change the energy structures of urban and rural areas, but also promote regional economic growth by creating an agglomeration effect, accelerating the flow of elements and so on. At the same time, the urbanisation process is affected in the reverse direction by regional economic and social development, such as the employment absorption capacity of urban industrial system, the population carrying capacity of a city, the level of agriculture development and the rural surplus labour force. These factors determine the speed of urbanisation and indirectly affect the degree of change caused by urbanisation in the regional energy consumption structure and $CO_2$ emissions. Then, from a systems point of view, the causal, two-way feedback system of urbanisation and economic development and the one-way effect system of urbanisation and $CO_2$ emissions are formed (Fig. 4).

With the development of economic society, as well as the technology progress and the living-style change, the differences of energy consumption of production and living between urban and rural areas are also changing. Therefore, regional carbon emissions caused by the urbanisation process will also change. How to calculate and simulate the effect of urbanisation on the regional carbon emissions change under the dynamic condition is the necessary and key link of revealing the internal effect mechanism and extent, as well as the current hot topics actively explored by academia.

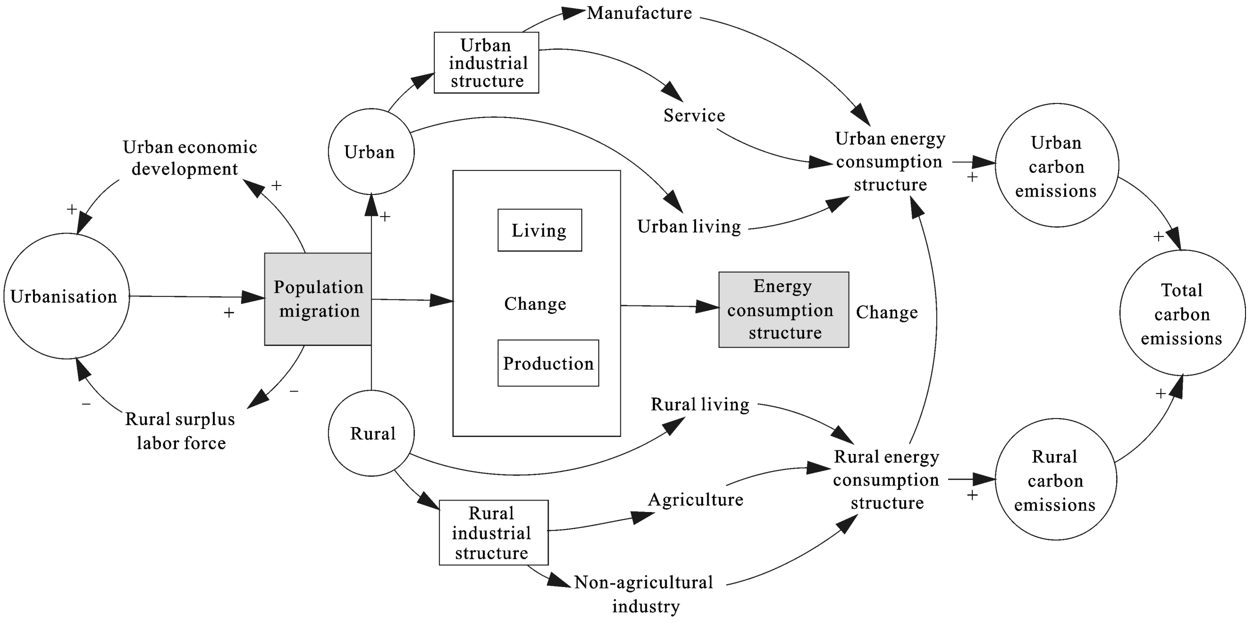

**Fig. 4** Effect of urbanisation on $CO_2$ emissions. Arrow means causal or interactive relationship. If change of variable causes the direction change of another variable, the symbol '+ ' is signed; oppositely, the symbol '– ' is signed

# 4 Model Building and Calculation

Based on the above-mentioned mechanism underlying the effect of urbanisation on regional energy consumption and $CO_2$ emissions, this study utilises a system dynamics model, combines the two response systems of urbanisation plus economic growth and urbanisation plus $CO_2$ emissions, and dynamically and quantitatively simulates the effect of the urbanisation process on the energy structure and $CO_2$ emissions in Liaoning Province. According to the cause and effect feedback loop path obtained through the mechanistic analysis (Fig. 4), the auxiliary parameters are set on the basis of the change trend of historical data and ′stock-flow′ equations are built.

## 4.1 Data sources

The main data come from *Liaoning Statistical Yearbook (1978–2012)* (Bureau of Statistics of Liaoning, 1979–2013), *Chinese Energy Statistics Yearbook* (National Bureau of Statistics of China, 1979–2013) and the internal data provided by the Liaoning Provincial People′ Government including the annual report data of more than 73 scale enterprises in fourteen cities and the questionnaire statistical results of ′residents income and household consumption in urban and rural areas′. The energy conversion coefficient and $CO_2$ emissions factor in the model are on the basis of the standards of the *Chinese Energy Statistics Yearbook* (National Bureau of Statistics of China, 1979–2013) and the 2006 IPCC Guidelines for National Greenhouse Gas Invent*ories* (IPCC, 2006). This study takes the actual data about $CO_2$ emissions of Liaoning Province from 1978 to 2012 as the historical basis for parameter setting, and chooses the period from 2013 to 2030 as the time period of the simulation.

## 4.2 Methods

Most of the existing research achievements regarding the effects of urbanisation on regional $CO_2$ emissions are their regression analysis, rather than causal logical derivation. Therefore, the actual mechanism underlying these effects is difficult to reflect, and the extent of the effect of urbanisation on $CO_2$ emissions and the rules determining the dynamic evolution of $CO_2$ emissions can not be accurately defined. Moreover, the urbanisation process and regional $CO_2$ emissions are two aspects of the regional development system that are affected by many factors, and they are both processes involving long-term, dynamic changes. Therefore, they require a mathematical model that can systematically and dynamically reflect, analyse and simulate their causal logic relationships.

The system dynamics method was created by Professor Forrester (1958) of Massachusetts Institute of Technology in the mid-1950s. After decades of development and improvement, this methodology is now widely used in studies on the economy, society, ecology and many complex systems (Li *et al.*, 2012b).

The mathematical kernel of system dynamics model is pluralistic integral equations, composed by level variable ($L$), rate variable ($R$) and auxiliary variable ($A$). Rate variables reflect the dynamic change of material or phenomenon with time, the level variables are the accumulation of rate variables and the auxiliary variables reflect the effect of other things on rate variables. The relevant formula can be simply described as:

$$L_t = L_{t-1} + R_t \tag{1}$$

$$R_t = F(A_t) \tag{2}$$

where $L_t$ is level variable in time $t$; $L_{t-1}$ is level variable in time $t$–1; $R_t$ is rate variable in time $t$; $A_t$ is auxiliary variable in time $t$.

With quantifiable and controllable characteristics, a system dynamics model can reveal the dynamics, feedback, delay and other processes of a system, and it has a distinct advantage in studies on the long-term dynamic variation of systems, system design, optimisation and management and other feedback effects of multisystem (Li *et al.*, 2005) . Therefore, this methodology meets the actual situation and modelling requirements of our study.

## 4.3 Setting of variables and parameters

The model includes 2 level variables, 2 rate variables and 62 auxiliary variables. The meaning of main variables, the calculation formulas and parameters setting are shown in Table 1.

## 4.4 Boundary hypothesis

The urban population will not increase limitlessly. When the rural labour force is not able to support growth in the agricultural GDP, i.e., when the disappearance of the rural surplus labour force affects the sustainable growth of agriculture, forestry, animal husbandry and fisheries

**Table 1** Setting of variables and parameters

| Main variables and parameters (meaning) | Calculation formulas |
|---|---|
| **Level variables:** | |
| Urbanisation rate | INTEG (Growth speed of urbanisation rate,0.6562) |
| Total population | INTEG (population growth,4374.18) |
| **Rate variables:** | |
| Growth speed of urbanisation rate | IF THEN ELSE (Time = 2012, Speed growth, IF THEN ELSE(Added value of Agriculture–Added value of agriculture last year≤0, Speed growth))<br>High speed scenario: Speed growth = 0.015; Intermediate speed scenario: Speed growth = 0.01; Low speed scenario: Speed growth = 0.005; |
| Population growth | Total population × Growth rate of population |
| **Auxiliary variables** | |
| FEC of UH (fossil fuel energy consumption of urban household) | Per capita FEC of UH × Urban population |
| FEC of UP (fossil fuel energy consumption of urban production) | Urban energy consumption × Proportion of FEC of UP |
| FEC of RH (fossil fuel energy consumption of rural household) | Per capita FEC of RH × Rural population |
| FEC of RA (fossil fuel energy consumption of rural agricultural industries) | Energy consumption of RA × Proportion of FEC of RA |
| FEC of RNA (fossil fuel energy consumption of rural non-agricultural industries) | Energy consumption in RNA × Proportion of FEC of RNA |
| $C_1$ (Carbon emission coefficient of oil) | 0.83632 |
| $C_2$ (Carbon emission coefficient of natural gas) | 5.95644 |
| $C_3$ (Carbon emission coefficient of coal) | 0.539426 |
| $C_4$ (Carbon emission coefficient of firewood) | 1.513 |
| CE of RA ($CO_2$ emissions of RA) | CC of RA × $C_3$ + OC of RA × $C_1$+ NGC of RA × $C_2$ |
| CE of RH ($CO_2$ emissions of RH) | NGC of RH × $C_2$+ CC of RH × $C_3$ + FC of RH × $C_4$ + OC of RH × $C_1$ |
| CE of RNA ($CO_2$ emissions of RNA) | OC of RNA × $C_1$+ NGC of RNA × $C_2$+ CC of RNA × $C_3$ |
| CE of UH ($CO_2$ emissions of urban household) | OC of UH × $C_1$+ CC of UH × $C_3$+ NGC of UH × $C_2$ |
| CE of UP ($CO_2$ emissions of urban production) | CC of UP × $C_3$+ NGC of UP × $C_2$+ OC of UP × $C_1$ |
| Added value of agriculture | Rural population × Per capita agriculture production capacity |
| Added value of agriculture last year | DELAY1(Added value of agriculture, 1 ) |
| Urban GDP | Per capita urban production capacity × Urban population |
| Urban energy consumption | Urban energy consumption per GDP × Urban GDP |
| Total fossil energy consumption | FEC of RA + FEC of RH + FEC of RNA + FEC of UH + FEC of UP |
| Total CE (Total $CO_2$ emissions) | (CE of RA + CE of RH + CE of UH + CE of RNA + CE of UP) × 44/12 |
| Rural added value of RNA | Rural population × Rural production capacity per capita of RNA |
| Energy consumption of RNA | Rural added value of RNA × Rural energy consumption per added value of RNA |
| Energy consumption of agriculture | Added value of agriculture × Energy consumption per unit added value of agriculture |
| OC of RA (oil consumption of RA) | FEC of RA × Proportion of oil used in RA/1.4286 |
| OC of RH (oil consumption of RA) | FEC of RH × Proportion of oil used in RH/1.4286 |
| OC of RNA (oil consumption of RNA) | FEC of RNA × Proportion of oil used in RNA/1.4286 |
| OC of UH (oil consumption of UH) | FEC of UH × Proportion of oil used in UH/1.4286 |
| OC of UP (oil consumption of UP) | FEC of UP × Proportion of oil used in UP/1.4286 |
| NGC of RA (natural gas consumption of RA) | FEC of RA × (1–Proportion of oil used in RA-Proportion of coal used in RA)/13.3 |
| NGC of RH (natural gas consumption of RH) | FEC of RH × Proportion of gas used in RH/13.3 |
| NGC of RNA (natural gas consumption of RNA) | FEC of RNA × (1–Proportion of coal used in RNA-Proportion of oil used in RNA)/13.3 |
| NGC of UH (natural gas consumption of UH) | FEC of UH × Proportion of gas used in UH/13.3 |
| NGC of UP (natural gas consumption of UP) | FEC of UP × (1–Proportion of coal used in UP-Proportion of oil used in UP)/13.3 |
| FC of RH (firewood consumption of RH) | FEC of RH × Proportion of coal used in RH/0.513 |
| Energy consumption of agriculture | Added value of agriculture × Energy consumption per unit added value of agriculture |
| Energy consumption in RNA | Rural added value of RNA × Rural energy consumption per unit added value of RNA |
| CC of RA (coal consumption of RA) | FEC of RA × Proportion of coal used in RA/0.7143 |
| CC of UP (coal consumption of UP) | FEC of UP × Proportion of coal used in UP/0.7143 |
| CC of UH (coal consumption of UH) | FEC of UH × (1–Proportion of oil used in UH–Proportion of gas used in UH)/0.7143 |
| CC of RNA (coal consumption of RNA) | FEC of RNA × Proportion of coal used in RNA/0.7143 |
| CC of RH (coal consumption of RH) | FEC of RH × (1–Proportion of coal used in RH–Proportion of gas used in RH–Proportion of oil used in RH)/0.7143 |

(and, thus, the added value of agriculture is less than that of last year), it becomes difficult for the population to transfer to cities. Therefore, the increase of the urbanisation rate is constrained by agricultural GDP growth in the model settings, and when the agricultural GDP is not increased or shows a decline, the urbanisation rate remains the same.

In addition, as same as other mathematical model, the system dynamics model also has some limitations. It must base on a fully understand of causality and a relatively stable system relationship. Therefore, this simulation of the future trend by the model is based on the following assumptions: 1) this model assumes that economic growth will not change dramatically due to huge outside impact; 2) the model assumes that the speed of technological progress and industrial development keeps stable and close with history, and not consider a huge leap or recession; 3) the model does not consider the large-scale foreign new type energy or large-scale energy mineral deposits; 4) the urbanisation is a complicated development process, and in order to highlight the research main body, the model only considers the effect of population migration on energy consumption structure, does not consider the large-scale investment from outside area or large production and construction projects which can affect the entire province′ economy structure.

According to the modelling principle, parameter settings and boundary hypothesis described above, the Urbanisation-Energy Consumption-$CO_2$ Emissions System Dynamics model (UEC-SD model) was built, and the model structure is shown in Fig. 5. Then, using these equations, the rural population, urban GDP, and the added value of agriculture and rural non-agricultural industry can be simulated and calculated. Subsequently, according to the energy consumption structures of different industries as well as those of urban and rural households, the production and living energy consumption and the $CO_2$ emissions in urban and rural areas can be calculated separately. And then the $CO_2$ emissions can be added together to obtain the regional total $CO_2$ emissions.

## 5 Scenario Analysis and Results

Although urbanisation can cause the change of $CO_2$ emissions, the urbanisation process of different speed can cause different development tracks of industry system,

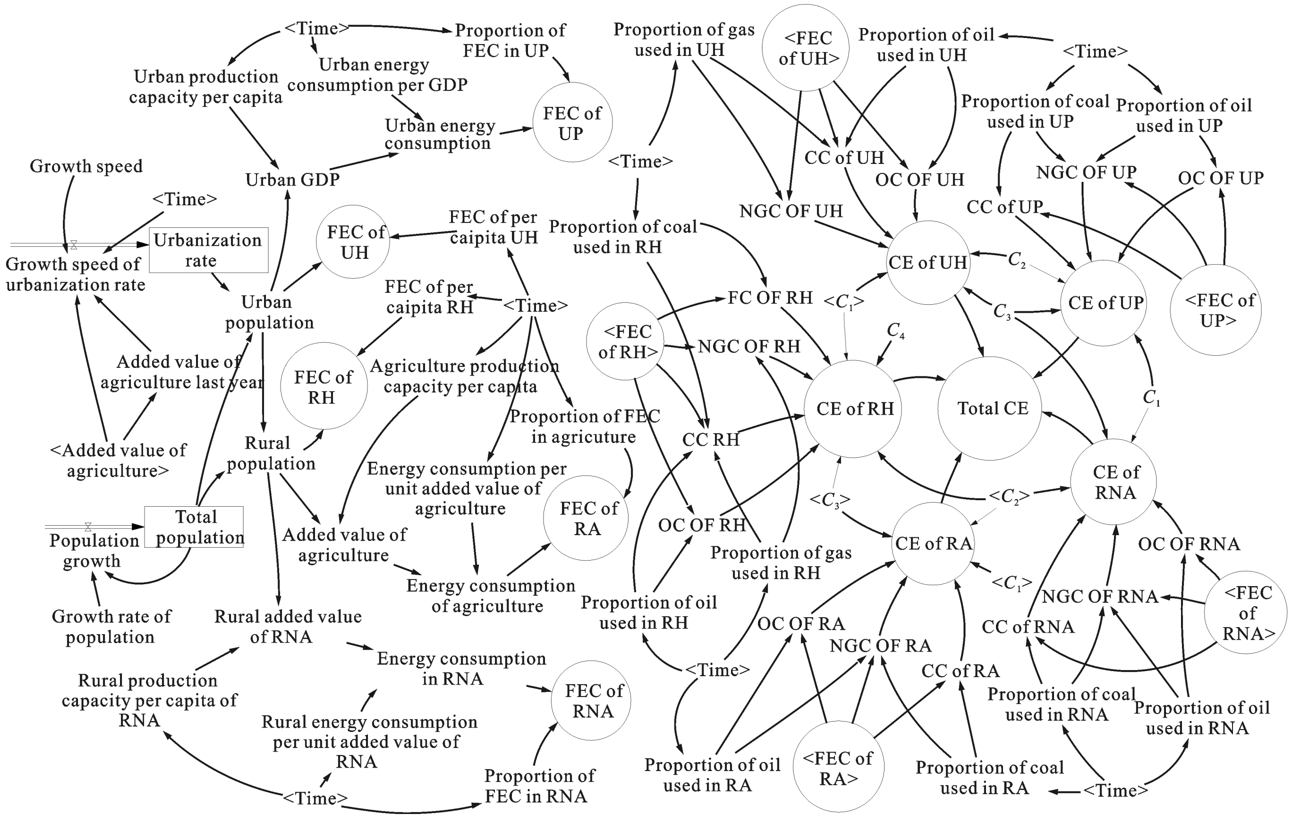

**Fig. 5** Structure of model. Abbreviations meaning of relevant variables are shown in Table 1

and then produces different energy consumption structure, resulting in the difference of $CO_2$ emissions amount and change trend under different urbanisation scenarios. We need to seek an urbanisation pattern and speed which can attain the goal of urbanisation and minimize the regional $CO_2$ emissions by comparing the changes of $CO_2$ emissions caused by different urbanisation speeds.

According to the current growth speed of urbanisation rate in Liaoning Province, when the urbanisation is gradually becoming close to 70%, in the future, the growth of the urbanisation rate in Liaoning Province will not accelerate continuously but will gradually tend toward stability. Therefore, by applying the UEC-SD model, the urbanisation rate is set for three scenarios: slow speed (annual growth rate of 0.5%), intermediate speed (annual growth rate of 1.0%) and high speed (annual growth rate of 1.5%). Subsequently, all types of energy consumption and $CO_2$ emissions under the three scenarios are calculated and simulated for 2013–2030 in the case study area, after which the regional energy consumption structure and $CO_2$ emissions under the three scenarios are compared and analysed. The simulations showed the following results:

Under the intermediate speed scenario, the urbanisation rate is 65.62% at the beginning of 2012 and will reach 82.62% to 2030. Then, due to the limitation of agricultural development requirements, it tends to be stable. Under the high speed scenario, the increase in the urbanisation rate will be restricted and will become slow in 2021, whereas if the speed of the growth of the urbanisation rate remains unchanged, the urbanisation rate will reach 85.12% in 2030. Finally, the slow speed scenario will not be restricted by agricultural development, and the urbanisation rate will reach 74.62% in 2030 (Table 2).

Under all of the different urbanisation scenarios, regional $CO_2$ emissions increase rapidly. The faster the urbanisation rate increases, the faster $CO_2$ emissions rise. However, under the intermediate and high speed scenarios, when the urbanisation rate reaches approximately 80%, $CO_2$ emissions will reach a peak value and then begin to decrease; i.e., when the urbanisation rate exceeds 80%, the higher the urbanisation level becomes, the lower $CO_2$ emissions will be. Under the low speed scenario, the urbanisation rate will not reach 80% before 2030, and $CO_2$ emissions increase continuously (Fig. 6).

Changes in regional total $CO_2$ emissions are caused by the changes in the fossil fuel energy consumption structure under the different scenarios. The urban fossil fuel energy consumption associated with production and living increases with an increasing urbanisation level,

**Table 2** Simulation results for fossil fuel energy consumption and $CO_2$ emissions under different urbanisation scenarios

| | Urbanisation rate （%） | | | Total fossil fuel energy consumption ($10^4$ t) | | | Total $CO_2$ emissions ($10^4$ t) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low speed | Intermediate speed | High Speed | Low speed | Intermediate speed | High speed | Low speed | Intermediate speed | High speed |
| 2012 | 65.62 | 65.62 | 65.62 | 28406.97 | 28406.97 | 28406.97 | 71536.59 | 71536.59 | 71536.59 |
| 2015 | 67.12 | 68.62 | 70.12 | 33098.96 | 33186.28 | 33273.60 | 82833.25 | 82986.71 | 83140.16 |
| 2020 | 69.62 | 73.62 | 77.62 | 38099.86 | 38493.32 | 38862.20 | 93454.12 | 94271.76 | 95029.13 |
| 2025 | 72.12 | 78.62 | 82.12 | 39957.91 | 40849.29 | 41272.18 | 97117.79 | 99101.47 | 100030.38 |
| 2030 | 74.62 | 82.62 | 85.12 | 40622.52 | 40878.08 | 41157.48 | 97440.75 | 97936.09 | 98573.07 |

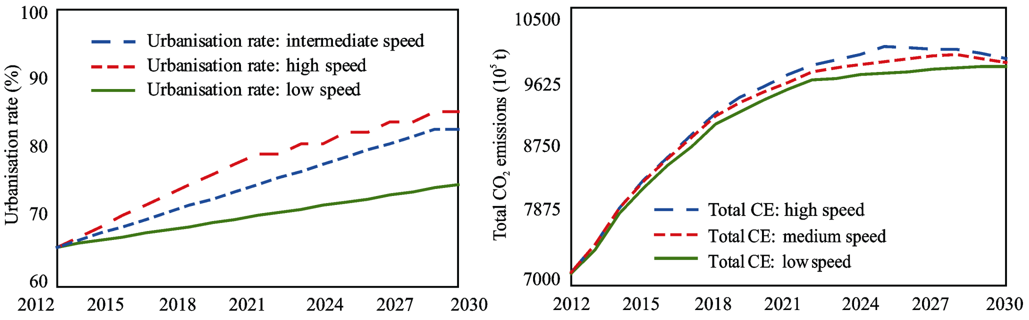

**Fig. 6** $CO_2$ emissions under different of urbanisation scenarios

and the faster the urbanisation rate increases, the greater the amount of consumption is. Under the intermediate and high speed scenario, agricultural fossil fuel energy consumption changes not very significant, while under the low speed scenario, it increases rapidly. Fossil fuel energy consumption in rural households and rural non-agricultural industries increase first and then decrease with an increasing urbanisation level and the faster the urbanisation rate increases, the lower the amount of consumption is (Fig. 7).

## 6 Conclusions

(1) Due to the large differences in the energy consumption structure associated with production and living in urban and rural areas, the urbanisation process in Liaoning Province has a great effect on the regional energy consumption structure. With an increase in the urbanisation rate, urban production and living energy consumption will rise first and then remain unchanged, while rural production and living energy consumption will decrease.

(2) With an increase in the urbanisation rate, the CO$_2$ emissions in Liaoning Province will rise in the short term. Then, when the urbanisation rate reaches 80% around, regional CO$_2$ emissions will reach a peak value and subsequently decrease. The faster the urbanisation rate increases, the higher the carbon emissions may become in Liaoning Province.

(3) The inflection point of CO$_2$ emissions in Liaoning Province appears later, when the growth of the urbanisation rate slows due to the restriction. This indicates that the effect of urbanisation on CO$_2$ emissions is not direct in Liaoning Province, and the urbanisation process affects CO$_2$ emissions through energy consumption, technology, economic growth, the industrial structure and so on.

(4) The simulation results of case area show that, the fossil energy consumption of unit population from urban areas is higher than that from rural areas in Liaoning Province. Therefore, the CO$_2$ emissions in the province will increase in the short term due to the urbanisation rate increase. But with the improvement of production technology and the promotion of clean energy, when the urbanisation rate reaches about 80%, the fossil energy consumption of unit population from urban areas is gradually lower than that from rural areas in Liaoning Province, thus the CO$_2$ emissions become decreased. This shows that the effect direction of urbanisation on the regional CO$_2$ emissions is not necessarily increased or decreased, but depends on the urbanisation stage and the proportion characteristics of the fossil energy consumption between rural and urban areas.

(5) The urbanisation process is very complicated, and the existing models are hard to simulate the whole process and the future. The model established can better reflect the inner mechanism and process about the effect of urbanisation on CO$_2$ emissions under the assumed

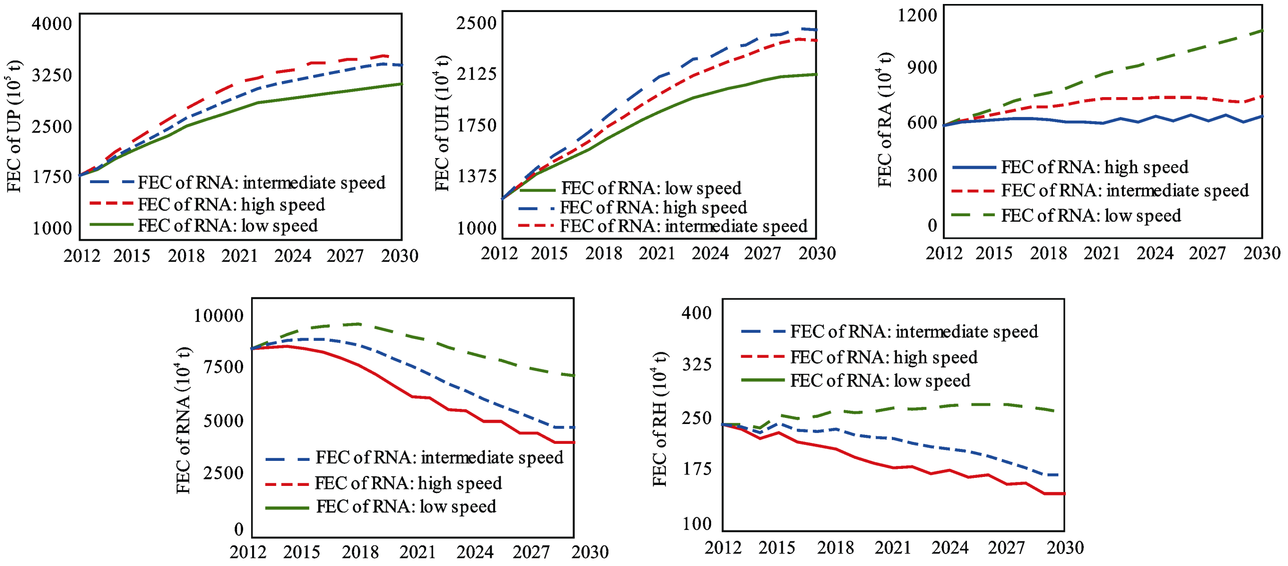

**Fig. 7** Changes in fossil fuel energy consumption associated with urban and rural production and living under different urbanisation scenarios. The abbreviations meaning of relevant variables are shown in Table 1

boundary. This has important reference significance for the relevant research on scientific measurement and prediction of the effect of urbanisation on regional energy consumption structure and $CO_2$ emissions.

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