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A Quick Measurement Method of Urban Low-Carbon Development: Energy Allocation Analysis, TRO Index, and Case Study of Beijing#

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ABSTRACT

Urban low-carbon development is a dynamic process requiring a systematic method to observe its progress continuously and quickly. The Energy Allocation Analysis (EAA) and TRO index established at national level can meet this requirement. The paper aims to develop an EAA-TRO method suitable for quickly analyzing urban low-carbon development and validate it by a case study of Beijing. Firstly, an EAA method is established for accounting the responsibilities of energy consumption and carbon emissions in the whole energy system. Secondly, TRO index is established to identify driving forces. The results of the case study indicate that Beijing's energy consumption rises from 69.9 Mtce (2017) to 71.2 Mtce (2021), with carbon emissions increasing from 146.6 to 154.8 Mt CO2. The energy supply shifts from coal to electricity and gas which totally account for 70.3% of emission responsibilities in 2021 and are mainly purchased from outside. Meanwhile, the energy consumption becomes more concentrated in buildings which accounts for 57.8% of emission responsibilities. Therefore, more attention must be paid to control building energy consumption and improve energy conversion efficiency while promoting electrification and coal reduction.

Keywords: urban low-carbon, low-carbon development, energy system, energy allocation analysis

NONMENCLATURE

Abbreviations	
TRO index	Total Amount Change - Relative Growth Rate - Occupation Ratio Change index
EAA	Energy Allocation Analysis
CEAA	Carbon Emission Allocation Analysis
PEQ	Primary Energy Quantity
PQ	Physical Quantity
SQ	Standard Quantity
CHP	Cogeneration, combined heat and power
Symbols	
β	Conversion coefficient for standard coal
k	Primary energy conversion coefficient
j	Energy type
E	Quantity of energy consumption
s	Process of energy structure
C	Carbon dioxide emission responsibility contained or generated
c	Carbon emission factor
T	Total amount change of the carbon dioxide emissions
R	Relative growth rate of total amount change
P	Proportion of the carbon dioxide emissions
O	Occupation ratio change of proportion
t	Year
n	A certain item, step or section

1. INTRODUCTION

Low-carbon development is an important and complex part of global climate change governance, which requires continuous updating and optimization of relevant policies. Low-carbon development requires reducing energy consumption, and the focus of energy consumption is on urban areas, so it is necessary to apply a quick measurement method of urban low-carbon development, used for observing and updating policies in the urban area.

In terms of low-carbon development, Pearson P J G, and Foxon T J [1] analyze from industry, Emberger G [2] from transportation, Zhang L et al. [3] from building, and Williams J [4] from resource cycling. The concept of urban low-carbon is generally believed to originate from low-carbon economy [5]. Dai Y [6], Fu Y et al. [7] propose urban low-carbon development pathways from multiple

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aspects. In addition to common qualitative methods, there are quantitative analysis methods using Logarithmic Mean Divisia Index I [8], but the data computation is large and the changes in end-use are not intuitive and clear enough. At present, some of the main related methods are simple qualitative analysis, while others are complex technical research with a large amount of computation, lacking policy grasp. TRO index [9] provides a quicker, more intuitive, quantitative and comprehensive measurement to evaluate structure changes. After combining with EAA, the new EAA-TRO method can be applied according to the characteristics of urban energy consumption.

The research contents of this paper mainly include: (1) EAA and carbon emission allocation analysis (CEAA) in Beijing, (2) analysis of changes and driving factors in carbon emissions in Beijing.

The main contributions lie in: (1) applying the EAA-TRO method to the urban level, achieving new methodological developments, and making revisions based on the characteristics of urban end-use energy consumption, (2) utilizing the EAA-TRO method to Beijing for case study, analyzing the latest progress and influencing factors of low-carbon energy development, and proposing policy implications that keep up with the times, which are excessive electrification can lead to high carbon emissions, and low-carbon development policies should be carefully designed and implemented.

2. METHODOLOGY

2.1 EAA and CEAA method

EAA method involves constructing an energy system model, including boundaries, sectors, stages, and relationships, to calculate energy balance and compile an energy balance sheet, which is often visualized by drawing an energy Sankey diagram. In this paper, energy loss accounts for a relatively small portion of urban energy consumption, therefore the Energy Allocation Sankey Diagram [10] is chosen.

Afterwards, a carbon emission balance can be constructed and a similar Sankey diagram of energy related carbon dioxide emission responsibility allocation can be drawn (hereinafter referred to as the "Carbon Emission Allocation Sankey Diagram").

2.2 TRO index method

TRO index is defined as an index that represents three dimensions: T (Total Amount Change), R (Relative Growth Rate), and O (Occupation Ratio Change) [9]. The formulas of calculation standards are as follows.

$$\mathrm{T}_n = C_{n,t_1} - C_{n,t_0} \tag{2-1}$$

$$\mathrm{R}_n = (C_{n,t_1} - C_{n,t_0})/C_{n,t_0} \tag{2-2}$$

$$\mathrm{O}_n = \mathrm{P}_{n,t_1} - \mathrm{P}_{n,t_0} \tag{2-3}$$

The subscript n represents the carbon emissions corresponding to a certain energy type with the subscript t_0 being the reference year (2017) and the subscript t_1 being the observation year (2021). The variable C represents the carbon emissions of the corresponding part in the subscript year, and the variable P represents the proportion of the carbon emissions of the corresponding part in the subscript year to the carbon emissions at the end-use of this part.

2.3 Data processing of energy

2.3.1 Data collection

The paper selects the "Beijing Energy Balance Sheet (PQ) -2017" from the "China Energy Statistical Yearbook 2018" [11] and the "Beijing Energy Balance Sheet (PQ) - 2021" from the "China Energy Statistical Yearbook 2022" [12] as energy balance sheets, and uses "the boundary 2" standard proposed by WRI [13] to calculate urban energy consumption and carbon emissions.

2.3.2 Data processing

Referring to the energy data processing method based on PEQ [8], the energy data is adjusted.

The conversion coefficient for standard coal β is introduced here, resulting in the conversion of PQ based measurement units into SQ based units (10k tons of standard coal) when multiplied by this coefficient. Then, the energy data based on PQ is adjusted to that based on SQ (the end-use of "heat" and "electricity" should be calculated based on local equivalent values, so no adjustment will be made here). Introducing the conversion coefficient of primary energy [8], k_j is defined as the quantity of *j* primary energy required to produce one unit of energy type. The formula for converting SQ based energy data into PEQ based is as follows:

$$E_{\mathrm{SQ},j} \cdot k_j = E_{\mathrm{PEQ},j} \tag{2-4}$$

Among them, $E_{\mathrm{SQ},j}$ represents the *j* energy quantity based on SQ for energy types, and $E_{\mathrm{PEQ},j}$ represents the *j* energy quantity based on PEQ for energy types. And it is stipulated that the k values of raw coal, crude oil, natural gas, and other energy sources are fixed at 1.

This paper combines "heating" and "thermal power generation" (referred to CHP), and calculates the primary energy conversion coefficient of "heat and electricity", 1.41 (2017) and 1.40 (2021) for results.

There is a large amount of purchased electricity in Beijing, which should be calculated separately. Here, the conversion coefficient of purchased primary energy k^0 is introduced, which has the same specific meaning as the conversion coefficient of primary energy k . Referring to the "Research on Carbon Dioxide Emission Factors of China's Regional Power Grid (2023)" [14], combined with weighted calculation of power generation structure, it is found that about 85.6% of Beijing's purchased electricity comes from thermal power generation, and the energy efficiency of power generation is 35%. Therefore, 85.6% / 35% = 2.4457, resulting in approximately 2.4457 kWh of original energy consumption per 1 kWh of actual electricity. Therefore, k^0 is equal to 2.4457.

Based on the above calculations and formula (2-4), all energy quantities based on SQ can be adjusted to energy quantities based on PEQ.

2.4 Data processing of carbon emissions

By introducing carbon emission factors for calculation, the energy quantity is converted into carbon emissions, $E_{\mathrm{PEQ},sj}$ representing the energy quantity based on PEQ of the j energy type in the s process, C_{sj} representing the carbon dioxide emission responsibility contained or generated by the j energy type in the s process. The calculation formula is shown in formula (2-5).

$$C_{sj} = c_{sj} \cdot E_{\mathrm{PEQ},sj} \tag{2-5}$$

According to the relevant contents of IPCC [15], the calculation method for carbon emission factor c_j of j energy type can be obtained. After substituting the values and performing unit conversion, the carbon emission factor c of various energy types can be obtained, shown in Table. 1 [11-12][16].

Table. 1 The carbon emission factors of various energy types. [11-12][16]
(Unit: ton of carbon dioxide / ton of standard coal)

Energy Type	*c*
Raw Coal	2.63
Briquettes	3.98
Coal Products	3.98
Coke	2.93
Crude Oil	2.11
Gasoline	1.99
Kerosene	2.05
Diesel Oil	2.13
Fuel Oil	2.22
LPG	1.81
Refinery Gas	1.93
Other Petroleum Products	2.15
Natural Gas	1.79
LNG	1.81

Heat and electricity are divided into two main parts: "import" and "local production". The heat of the former part is based on the carbon emission factor of natural gas as a reference in the local production process, and the carbon emission factor of electricity refers to the power generation structure of primary energy [14]. After calculation, the carbon emission factor c of the "import" portion of electricity in Beijing are 2.47 tons of carbon dioxide per ton of standard coal (2017) and 2.88 tons of carbon dioxide per ton of standard coal (2021) based on PEQ energy data standards.

3. CASE STUDY AND RESULTS

3.1 EAA and CEAA method application

The Sankey diagrams drawn consist of the energy supply, energy conversion, and energy end-use consumption. The energy end-use consumption is divided into three sections: production, building, and transportation. Referring to the calculation standards of Wang Q [17] and Chong C H [8], the energy data based on PEQ will be merged and adjusted, and will be visualized as the Sankey diagrams of EAA in Beijing for 2017 and 2021 by e!Sankey software, as shown in Fig. 1 and Fig. 2.

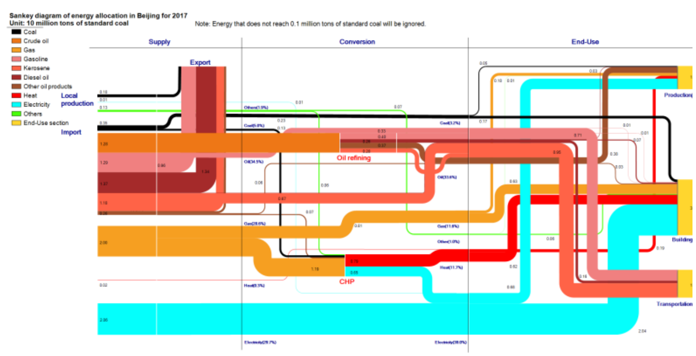

Fig. 1 Sankey diagram of EAA in Beijing for 2017.

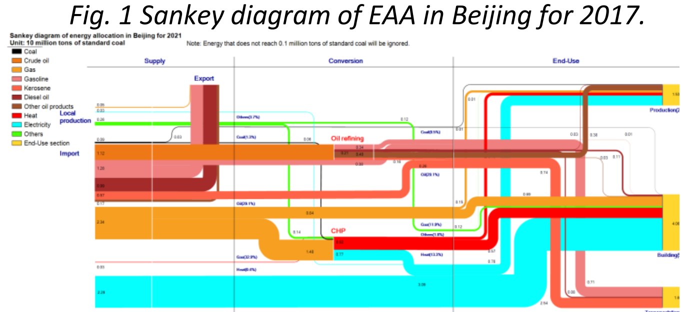

Fig. 2 Sankey diagram of EAA in Beijing for 2021.

Through the carbon emission factor method for calculating carbon emissions, the Sankey diagrams of CEAA in Beijing for 2017 and 2021 are shown in Fig. 3 and Fig. 4.

3.2 TRO index method application

The calculation results of the total carbon emission changes in Beijing from 2017 to 2021 are: $\mathrm{T_{total}}$ = 8.3 Mt CO_2, $\mathrm{R_{total}}$ = 5.7%. In order to evaluate the changes in carbon emission structure, 2017 is used as the reference year and 2021 is used as the observation year to calculate. The carbon emission changes of important parts and related energy types are measured, shown in Table. 2 for results, where the units of C_{n,t_0}, C_{n,t_1}, T_n are 10 Mt CO_2, and the subscripts n are represented by overall, specific step or section and energy type.

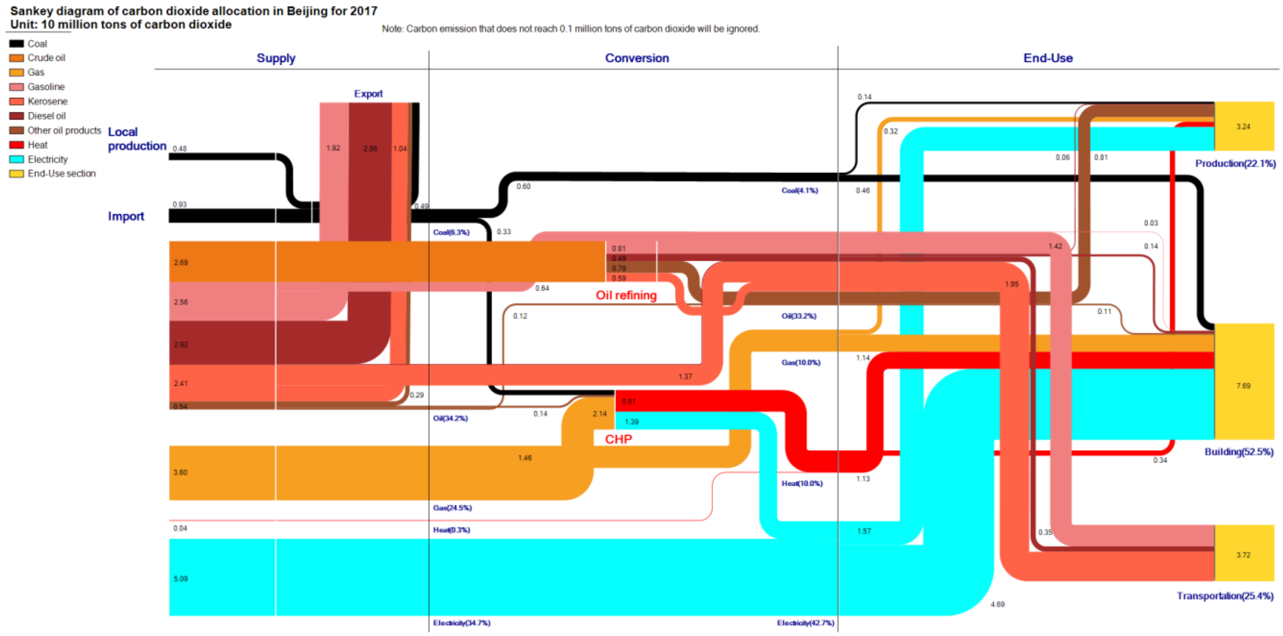

Fig. 3 Sankey diagram of CEAA in Beijing for 2017.

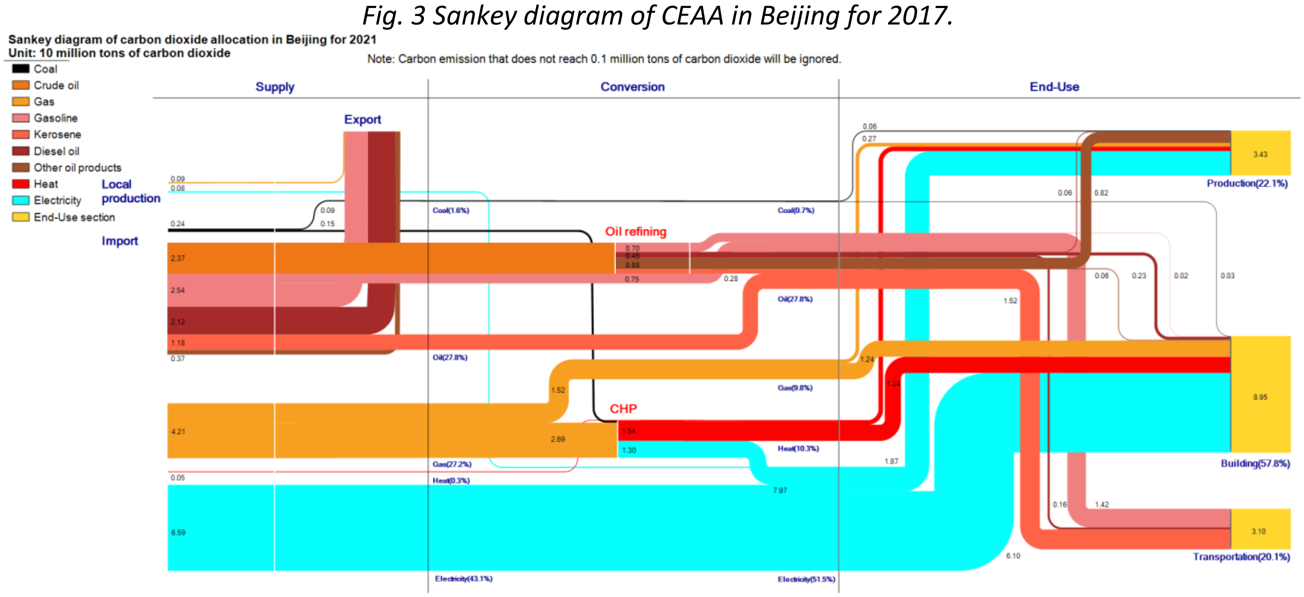

Fig. 4 Sankey diagram of CEAA in Beijing for 2021.

Table. 2 The calculation results of TRO index.

n			*Raw Data*				*TRO Index*		
Overall	*Specific Step / Section*	*Energy Type*	C_{n,t_0}	C_{n,t_1}	P_{n,t_0}	P_{n,t_1}	T_n	$\mathrm{R}_n(\%)$	$\mathrm{O}_n(\%)$
All	All (excluding export)	All	14.65	15.48	-	-	0.83	5.7	-
Supply	All (excluding export)	Coal	0.92	0.25	6.3%	1.6%	-0.67	-72.6	-4.7
Supply	All (excluding export)	Oil	5.02	4.30	34.2%	27.8%	-0.72	-14.4	-6.5
Supply	All (excluding export)	Gas	3.60	4.21	24.5%	27.2%	0.61	17.1	2.6
Supply	All (excluding export)	Heat	0.04	0.01	0.3%	0.0%	-0.03	-86.2	-0.2

Supply	All (excluding export)	Electricity	5.08	6.67	34.7%	43.1%	1.59	31.2	8.4
Supply	Local production (excluding export)	All	0.00	0.08	0.0%	0.5%	0.08	-	0.5
Supply	Import (excluding export)	All	14.65	15.40	100.0%	99.5%	0.75	5.1	-0.5
Supply	Import (excluding export)	Coal	0.93	0.25	6.4%	1.6%	-0.68	-72.8	-4.7
Supply	Import (excluding export)	Oil	5.02	4.30	34.2%	27.9%	-0.72	-14.4	-6.3
Supply	Import (excluding export)	Gas	3.60	4.21	24.5%	27.3%	0.61	17.1	2.8
Supply	Import (excluding export)	Heat	0.04	0.01	0.3%	0.0%	-0.03	-86.2	-0.2
Supply	Import (excluding export)	Electricity	5.08	6.67	34.7%	43.3%	1.59	31.2	8.6
Conversion	Oil refining	All	2.69	2.37	18.4%	15.3%	-0.32	-11.8	-3.0
Conversion	CHP	All	2.61	2.84	17.8%	18.3%	0.23	8.9	0.5
End-Use	All	Coal	0.60	0.10	4.1%	0.7%	-0.50	-83.0	-3.4
End-Use	All	Oil	4.86	4.30	33.2%	27.8%	-0.57	-11.6	-5.4
End-Use	All	Gas	1.46	1.52	10.0%	9.8%	0.06	4.1	-0.1
End-Use	All	Heat	1.47	1.60	10.0%	10.3%	0.13	8.6	0.3
End-Use	All	Electricity	6.26	7.97	42.7%	51.5%	1.71	27.3	8.7
End-Use	Production	All	3.24	3.43	22.1%	22.1%	0.18	5.7	0.0
End-Use	Production	Coal	0.14	0.05	4.4%	1.4%	-0.10	-67.4	-3.0
End-Use	Production	Oil	0.86	0.88	26.6%	25.6%	0.02	1.8	-1.0
End-Use	Production	Gas	0.32	0.28	9.9%	8.1%	-0.04	-13.6	-1.8
End-Use	Production	Heat	0.34	0.36	10.6%	10.4%	0.01	4.0	-0.2
End-Use	Production	Electricity	1.57	1.87	48.4%	54.5%	0.30	18.9	6.0
End-Use	Building	All	7.69	8.95	52.5%	57.8%	1.26	16.4	5.4
End-Use	Building	Coal	0.46	0.06	6.0%	0.6%	-0.40	-87.8	-5.4
End-Use	Building	Oil	0.28	0.31	3.6%	3.5%	0.04	13.6	-0.1
End-Use	Building	Gas	1.14	1.24	14.8%	13.9%	0.10	9.1	-0.9
End-Use	Building	Heat	1.13	1.24	14.6%	13.8%	0.11	10.0	-0.8
End-Use	Building	Electricity	4.69	6.10	61.0%	68.2%	1.41	30.1	7.2
End-Use	Transportation	All	3.72	3.10	25.4%	20.1%	-0.62	-16.6	-5.4
End-Use	Transportation	Gasoline	1.42	1.42	38.1%	45.9%	0.00	0.2	7.7
End-Use	Transportation	Kerosene	1.95	1.52	52.4%	48.9%	-0.43	-22.2	-3.5
End-Use	Transportation	Diesel Oil	0.35	0.16	9.5%	5.3%	-0.19	-53.6	-4.2

4. CONCLUSIONS AND DISCUSSIONS

The above results indicate that the most obvious among the new features is the growth of purchased electricity (import) in various parts, the continuous "electrification" of energy in Beijing and the increase in carbon emissions, as well as the sustained effect of "Zero Coal" [18] and the expansion of gas-fired power generation [19].

The driving factors can be summarized as follows: (1) in the supply part, policies have led to a sharp decrease in coal imports, while the increase in natural gas imports supports the clean energy transformation, (2) in the conversion part, the outbreak of COVID-19 has led to a decrease in oil demand, which may be due to the investment of new power generation units and an increase in power generation, (3) in the end-use part, policies and energy demand are similar to the supply part.

Policy implications are summarized as follows: (1) Beijing needs to control the energy consumption of buildings and the tertiary industry, as well as the demand for purchased electricity, to prevent high carbon emissions caused by excessive electrification, (2) Beijing needs to improve the energy efficiency in technology and break through the large-scale application of new technologies and low-carbon infrastructure settings, (3) other cities need to optimize industrial structure and building energy efficiency, control carbon emissions, and improve linkage measures among different departments of municipal government in order to integrate electrification with energy-saving and proceed rhythmically.

In summary, the EAA-TRO method can quickly measure the urban low-carbon development. Through case studies of Beijing, new discoveries can be made for low-carbon development, and new policy implications can be provided.

In further work, a more general method is needed when dealing with the carbon emission responsibilities from purchased electricity. Meanwhile, the end-use part can be further refined and divided for application in more regions. Additionally, methods and policy implications should be improved in conjunction with urban energy substitution and policy feedback.

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