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What lessons and experiences can be learned from China for practicing low carbon city: A policy instrument perspective

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ABSTRACT

Practicing low carbon city (LCC) is the key strategy for reducing carbon emissions in China. Policy instruments are important tools to guide LCC practice. Most existing studies failed to demonstrate the performance of LCC policy instruments in China. This study analyzes the lessons and experiences of Chinese cities for implementing LCC from the policy instrument perspective. This study developed a comprehensive two-dimensional analytical framework to classify policy instruments for LCC based on considerations of both diversity and abundance. Empirical analyses were conducted using data collected from 35 sample cities in China spanning the period from 2006 to 2020. The empirical findings reveal significant heterogeneity in the implementation of LCC policies across Chinese cities with varying levels of economic development. This research draws a holistic picture of LCC policy instruments in China, which can provide important references for governors to formulate targeted low-carbon policies.

1. Introduction

Carbon reduction in Chinese cities is of great importance for achieving global carbon reduction targets. According to a study by Crippa et al. [1], China has become the world's largest carbon emissions emitter since 2007, accounting for 29.7 % of global carbon emissions in 2018 [2]. While 80 % of carbon emissions in China come from cities. As the urbanization rate increases, China's urban carbon emissions will continue to rise [3–5]. Therefore, the Chinese government attaches great importance to reducing emissions at the city level. China has made significant efforts in mitigating carbon emissions through active development of renewable energy as a substitute for fossil fuels, which serves as a crucial pathway towards achieving its target of "carbon peaking 2030, carbon neutrality" [6,7]. The implementation of low-carbon cities is the main strategy to reduce urban carbon emissions. The National Development and Reform Commission in China has successively implemented three batches of low-carbon pilot projects, and a total of 81 cities have been selected as low-carbon pilot projects in China [8–10]. As the 'dual carbon' goal of reaching a carbon peak by 2030 and carbon neutral by 2060 is set by the government [2,11], reducing carbon emissions has become an important issue for both central and local governments in China. It is foreseeable that Chinese city managers will make more efforts in practicing low carbon city (LCC) in the future to achieve the "dual carbon" goal.

It is well appreciated that policy instruments are important means of achieving policy goals set by the government [12]. To implement LCC, many policy instruments have been formulated and implemented by the central and local governments. Only scientific and reasonable policy instruments can guide LCC practice effectiveness, while ineffective policy instruments will make LCC practice fall into a blind situation [13]. A large number of LCC practices have been carried out in Chinese cities since 2007 to reduce urban carbon emissions. According to the Peking University Law Database, the most comprehensive law and policy database in China, the number of LCC policy documents in China has increased rapidly from 1 in 2007 to 622 in 2020. However, the experiences and lessons of LCC policy instruments in China have not been displayed. For example, there are various shortcomings of low carbon policy instruments in China as pointed out by existing research. For example, Sheng [14] argued that the incomplete system, unreasonable structure, single type and insufficient enforcement are the main problems of the LCC policy instrument in China. Zhao [15] opined that the LCC policy instrument in China has the following shortcomings:

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weakness in subsidies instrument, lack of restricted policies and small tax policy intensity. The overall shortcomings and deficiencies of policy instruments in China can be identified by analyzing temporal evolution. By conducting spatial difference analysis, cities with better performance in LCC policy instruments can be identified for experience sharing, and ineffective experience sharing from cities with poor performance can be avoided [3].

However, most of the existing studies have failed to fully demonstrate the performance of LCC policy instruments in China. To address these issues and fill the existing gap in China's LCC policy research, this paper aims to reveal the spatial-temporal evolution of LCC policies in China by addressing three objectives: (1) Proposing a two-dimensional framework of abundance and diversity to analyze the performance of LCC policy in different cities. (2) Demonstrating the experience and lessons learned from policy instruments in China through temporal-spatial evolution analysis. (3) Providing policy suggestions based on temporal-spatial evolution analysis. The contributions of this study are as follows. Theoretically, it presents a framework for analyzing the performance of LCC policies utilizing a dual-perspective policy approach, which offers a fresh perspective for LCC research. Practically, this paper provides valuable insights from its temporal-spatial analysis of policy instruments in China, which can serve as a useful reference for local governments in formulating targeted low-carbon policies. The overall structure of this paper is organized as follows. Section 2 provides a literature review. Section 3 demonstrates the research methodology used to identify and analyze LCC policy instruments. Section 4 presents results and analysis of the experiences and lessons in China by exploring the temporal and spatial evolution of policy instruments. Section 5 will discuss the lessons learned from the existing policy instruments and experience learned from advanced areas best practices, followed by Section 6 to conclude this study.

2. Literature review

Policy instruments are the means to achieve policy objectives, and policy instrument analysis is one of the most commonly used methods in policy research [12]. By conducting the literature review, there are three mainstreams of research on LCC policy instruments, shown as follows.

The first category of existing research analyzes the performance of a particular type of LCC policy and proposes a series of policy implications to improve the performance of the type of policy [16]. For instance, the implementation of carbon tax and cap-and-trade systems has garnered significant scholarly attention in recent years as two pivotal policies for mitigating emissions [17];[18]. Li [19] analyzed China's market incentive LCC policies and found that carbon taxes, subsidies, carbon trading, carbon finance and carbon tariffs are the main LCC market incentive policies in China. Gao & Guo [20] analyzed China's carbon tax policies for LCC implementation and concluded that all fossil fuels, such as coal, natural gas and refined oil products, should be identified for taxation; and entities and individuals using fossil fuels should be identified as taxpayers. Peng [21] analyzed the fiscal and tax policies of low-carbon agriculture in China and concluded that insufficient investment, inadequate agricultural subsidy system and insufficient investment in agricultural science and technology are the main problems. Zhang et al. [22] proposed a series of market-based policies based on the performance of LCC economic policies in China, such as industrial and technological upgrading, carbon emission tax implementation, and increasing the cost of car use.

The other category of existing research analyzes the distribution of different LCC policy instruments and proposes strategies to improve LCC policies [16,23][24]. For example, Sheng [14] collected LCC policies issued by the central and local governments in China and found that the LCC policy instruments in China have the following shortcomings: inadequate systems, unreasonable structures, single types and insufficient implementations. Luo et al. [25] studied the composition of LCC policies in China based on co-word analysis, and concluded the following: there are too many administrative policies, and a lack of investment and financing policies. Luo et al. [26]conducted a quantitative study of China's LCC policy instruments by collecting 48 policy documents from the Peking University Law database. The research shows that there are problems of insufficient flexibility of regulatory policies, few property auction policies in economic incentive policies, and insufficient government guidance in China. Schaffrin et al. [27] measured the number and effects of climate-change-related policy instruments, and showed that these policies had distributional effects on energy-related industries, public opinion and government agencies. Auld et al. [28] conducted a systematic review of 292 policies that promote low-carbon technologies. The study found that policies with more flexible implementation schedules had more positive effects, while self-regulatory policies required trade-offs between costs, problems, and efficiency. Zhao [15] established a policy analysis framework for LCC policies in China from the perspective of "carbon industrial policy instrument" and "carbon environment policy instrument". The results showed that weak subsidies and insufficient restrictions are the main problems in policy instruments for the carbon industry, and weak tax policies are the major shortcomings of China's carbon environment policy instruments.

In addition, some scholars have combined LCC policy instruments with the effects of LCC practice to propose LCC promotion strategies based on optimal policy combinations. For example, Mao et al. [29] established a policy analysis framework from a two-dimensional perspective of "policy tools-outcomes of LCC practice". The findings suggest that the key objective of LCC practice in China is the development of low-carbon technologies and low-carbon energy. Mandatory policy instruments are the most common policy instruments used by local governments in China, while voluntary policy instruments are seldom used. Ma et al. [30] constructed an analytical framework of policy instruments for low-carbon cities and used a fuzzy set of qualitative comparative analyses to explore the configuration of existing policy instruments and their impact on LCC practices. By analyzing the application of the analytical instrument framework of 35 low-carbon pilot cities in China, the following conclusions were drawn: Market-based and network-based instruments are complementary to hierarchical instruments, while the combination of hierarchical and market-based instruments often hinders the role of network instruments and information instruments. Few network instruments have been used to practice LCC in China.

Table 1 illustrates a comprehensive comparison between the proposed approach and relevant literature contributions. As shown in Table 1, existing research on LCC policy instruments are scattered analysis of performance in a particular type of policy instrument or proposes a framework for analyzing the overall distribution of LCC policy instruments in China at a particular time interface. It is difficult to accurately improve the effectiveness of LCC policy instruments by only examining a particular type of policy instrument or the overall policy instrument in China. There are gaps in the existing studies in identifying experiences and lessons of the LCC instruments in China. Therefore, this study will identify the strengths and weaknesses of LCC policy instruments in China by analyzing the policy instruments for practicing LCC in terms of temporal and spatial evolution, and then propose

Table 1
Comparison between the proposed approach and the literature reviewed.

References	Research objective	Research Methods
Li [19]	LCC market incentive policies	Qualitative inorganic analysis
Gao & Guo [20]	Carbon tax policies	Qualitative inorganic analysis
Peng [21]	Low-carbon agriculture policies	Compensatory role analysis
Zhang et al. [22]	LCC economic policies	Qualitative inorganic analysis
Luo et al. [25]	Low-carbon industry financial policy	Co-word analysis
Zhai et al. [23]	LCC digital transformation policies	Text analysis
Auld et al. [28]	LCC technology policies	Systematic review
Sheng [14]	LCC policies at the central level	Text analysis
Luo et al. [26]	LCC policies at the central level	Quantitative research
Schaffrin et al. [27]	LCC policies at the national level	Analyzing policy density and intensity
Zhao [15]	LCC policies at the national level	Analysis of the industrial and environmental policies
Mao et al. [29]	LCC Policies in Qihe County	Analysis of policy objectives and policy types
Ma et al. [30]	LCC policy instruments for 35 low carbon pilot Chinese cities in 2018	Fuzzy set qualitative comparative analysis
Proposed approach	LCC policy instruments in 35 low carbon pilot Chinese cities from 2006 to 2020	A two-dimensional analytical framework for diversity and abundance from a time-evolving perspective

tailored policy implications.

3. Methodology

Based on the above research objectives, three research steps are designed in this study following the content analysis approach, including 1) Collecting and coding policy documents on practicing LCC in China. 2) Classification of the collection policy instruments according to the policy classification framework. 3) Analyzing and discussing the results. The analysis and discussion in this study are mainly based on the principle of experience mining. The weakness of policy instruments in China can be identified by analyzing the temporal and spatial evolution of LCC policy instruments in China. By learning from the experience of best performing pilot cities, Tail-made LCC policy implications are proposed to improve the performance of LCC policy instruments in China. The studies by Sun et al. [31] and Zhang et al. [32] have highlighted that greater policy diversity entails more types of policies, while a higher policy abundance implies an increased number and intensity of policies. Diverse and robust policies can enhance public attention towards LCC practice, thereby advancing its level [33]. Hence, irrespective of regional economic disparities, cities should be encouraged to adopt diverse policies and measures for promoting LCC. Consequently, through an analysis of policy diversity and abundance across different cities, this study suggests that cities lacking in diversity should incorporate additional policy categories. Similarly, cities with insufficient abundance should augment their policy supply to boost LCC performance by enhancing a number of related policies.

3.1. Method for identifying policy instruments

3.1.1. Typical policy instruments analysis framework

Policy instruments are the various measures taken by the government to achieve its desired governmental objectives. Kirschen et al. [34] first introduced the concept of policy instruments and divided them into 64 groups for the first time, which led scholars to explore the study of policy instruments. Peters and Nispen [35] stated that policy instruments are a set of specific measures to promote social development. According to Peters and Nispen [35], policy instruments are not only an important means for governments to guide economic and social development, but also serve as a bridge between policy objectives and policy applications. Typical policy instrument analysis frameworks are shown in Table 2.

3.1.2. Policy instruments analysis framework selection

Among the existing classification frameworks, the classification of policy instruments proposed by Howlett and Ramish [43] has been widely used in policy discipline [12,44,45]. The classical framework has been enhanced by other researchers when conducting studies on environmental policies [46,47]. Therefore, this study primarily adopts the classification proposed by Howlett and Ramish [43], while incorporating advancements from Sun et al. [46] and Chai et al. [47]. This forms the policy tool analysis framework presented in the following text. Based on the chosen framework for classifying policy instruments, policy instruments are classified into three categories, namely, mandatory policy instruments ($P_{I\text{-}A}$), voluntary instruments ($P_{I\text{-}B}$) and hybrid instruments ($P_{I\text{-}c}$). Mandatory policy instruments are tools that the government uses to implement public policies through its authority and compulsory power, typically performed as regulations or permits. Voluntary policy instruments ($P_{I\text{-}B}$) rely on individuals, families, social organizations, or markets to address public problems voluntarily. Hybrid policy instruments ($P_{I\text{-}c}$) combine elements of both mandatory and voluntary approaches by allowing some degree of government intervention while still leaving decisions up to non-governmental actors. These hybrid approaches often take the form of incentive policies. The level of government intervention is highest with mandatory policy instruments ($P_{I\text{-}A}$), followed by hybrid policy instruments ($P_{I\text{-}C}$), and lowest with voluntary policy instruments ($P_{I\text{-}B}$). The specific policy instruments included under each policy instrument type are shown in Table 3.

Table 2
Typical policy instrument analysis frameworks.

Reference	Policy instrument analysis framework
Lowi [36]	● Regulatory and non-regulatory instruments.
McDonnell & Elmore [37]	●Imperative instruments, incentive instruments, capacity building instruments and system change instruments.
Opschoor et al. [38]	●Command-and-control instruments, economic incentive instruments, and persuasion instruments.
Vedung & Doelen[39]	●Regulatory instruments, fiscal incentives and information transfer instruments.
World Bank [40]	●Mandatory management instruments, financial incentives, and voluntary planning instruments
Chen [41]	●Marketing instruments, business management technology and socialization instruments.
Howlett [42]	●Voluntary instruments, compulsory instruments and mixed instruments.

Source: sorted by the author according to corresponding literature.

Table 3
Policy instruments and their classification.

Types	Policy instruments	Expression Forms
Mandatory instrument ($P_{I\text{-}A}$)	●Regulatory instrument ($P_{I\text{-}A1}$)	Regulations, statutes, supervision, assessment, evaluation, sanctions, permits, formulation and adjustment of system rules and standards
	●Direct supply instrument ($P_{I\text{-}A2}$)	Government purchase, public financial payment and transfer, direct s ervice and management
	●Authoritative instrument ($P_{I\text{-}A3}$)	Guidance, implementation, planning, institution setting and reforming, government agreements and practices
Voluntary instrument ($P_{I\text{-}B}$)	●Individual household and Community instrument ($P_{I\text{-}B1}$)	Individual and family participation, social supervision.
	●Voluntary Organization and Service instrument ($P_{I\text{-}B2}$)	Volunteers, non-profit organization
	●Market instrument ($P_{I\text{-}B3}$)	Market regulation and competition
Hybrid instrument ($P_{I\text{-}c}$)	●Information and advocacy instrument ($P_{I\text{-}C1}$)	Public opinion establishment and publicity, encouragement, guidance, appeal, information release and disclosure, model demonstration, education
	●Incentive instrument ($P_{I\text{-}C2}$)	Decentralization, simplification of procedures, social prestige, retained earning
	●Subsidy instrument ($P_{I\text{-}C3}$)	Subsidy, tax, interest rates and other incentives, donations, financial in-kind incentives, subsidized loans

Source: Howlett and Ramish [42]; Sun et al. [46]; Chai et al. [47].

3.1.3. Method for analyzing the evolution of policy instruments

Previous studies have used species diversity and abundance index from the field of species studies as indicators to describe the direction, speed and degree of species succession [48]. Further research works have modified species diversity and abundance index in fields other than ecology, for example, the species diversity index has been applied to archaeology [49]. The concept of diversity reflects the number of individuals within a research scope and can effectively capture the scale effect of the research objects, while abundance represents the variety of types indicating resilience against external pressures. By considering these two perspectives, a comprehensive assessment of the current state of a system can be described. Evolution in the number, type, and structure of policy instruments can be observed by comparing the diversity and abundance index. Drawing on the concepts of the two indicators, this paper designs a species diversity-abundance index of LCC policies to describe the evolution of LCC policy instruments, the abundance of LCC policy was presented by the number of policy instruments and the diversity of LCC policy was described in terms of species of policy instruments.

The Boston Consulting Group (BCG) Matrix is a well-known method for analyzing and planning a firm's product portfolio, pioneered by Bruce Henderson in 1970 [50]. The core of this approach lies in classifying products into four types through the interaction of two factors and the development strategy for each type. It has been widely recognized by scholars for decades, and used by many researchers to classify research phenomena [51–53]. Therefore, the performance of LCC policy instruments in the sample cities was classified into four categories based on the BCG Matrix, namely, Category I (High Abundance-High Diversity); Category II (High Abundance-Low Diversity); Category III (Low Abundance-Low Diversity); Category IV (Low Abundance-High Diversity). The X-axis represents the degree of diversity in LCC policy instruments, while the Y-axis indicates the abundance of such instruments. The selection of average as a benchmark serves to provide a neutral and easily comprehensible reference point for the identification and analysis of LCC policy instruments, referring to the study by Du et al. [2], as detailed in Fig. 1.

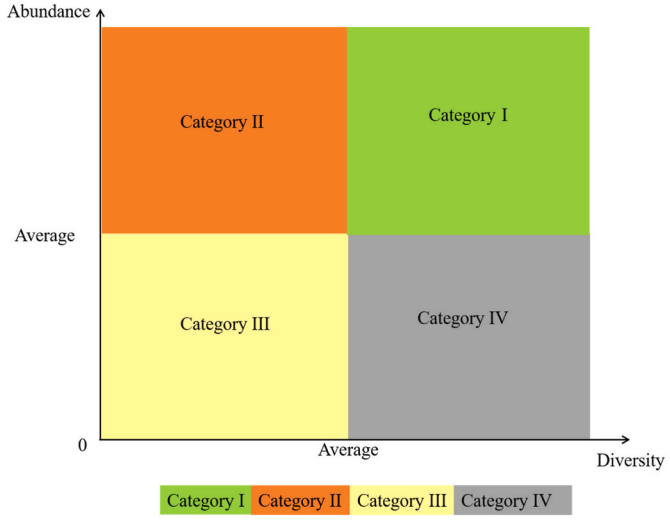

Fig. 1. A two-dimensional perspective analysis method for classifying LCC policy instrument.

3.2. Research data

3.2.1. Sample cities

There are over 300 prefecture-level cities in China and 35 megacities were selected as sample cities to reflect the LCC policy in China. The 35

Table 4
Policy instrument of 35 sample cites in China (Parts of the result).

Policy instruments	Policy Analysis Unit
$P_{I\text{-}A1}$	$P_{1\text{-}11}$、$P_{1\text{-}13}$、$P_{1\text{-}15}$、$P_{1\text{-}22}$、$P_{1\text{-}27}$、$P_{1\text{-}32}$、$P_{1\text{-}47}$、$P_{1\text{-}52}$、$P_{10\text{-}14}$、$P_{10\text{-}15}$、$P_{10\text{-}25}$、$P_{10\text{-}32}$、$P_{10\text{-}45}$、$P_{13\text{-}1}$、$P_{14\text{-}12}$、$P_{17\text{-}1}$、$P_{22\text{-}22}$、$P_{22\text{-}26}$、$P_{22\text{-}33}$、$P_{23\text{-}25}$、 …… 、$P_{34\text{-}6}$、$P_{34\text{-}9}$
$P_{I\text{-}A2}$	$P_{1\text{-}34}$、$P_{10\text{-}40}$、$P_{11\text{-}6}$、$P_{12\text{-}10}$、$P_{12\text{-}3}$、$P_{13\text{-}19}$、$P_{13\text{-}22}$、$P_{13\text{-}27}$、$P_{14\text{-}13}$、$P_{14\text{-}19}$、$P_{14\text{-}39}$、$P_{14\text{-}43}$、$P_{14\text{-}8}$、$P_{15\text{-}3}$、$P_{15\text{-}4}$、$P_{16\text{-}14}$、$P_{17\text{-}6}$、$P_{17\text{-}7}$、$P_{18\text{-}17}$、$P_{19\text{-}13}$、 …… 、$P_{32\text{-}9}$、$P_{32\text{-}10}$、$P_{34\text{-}11}$、$P_{34\text{-}15}$、$P_{34\text{-}16}$
$P_{I\text{-}A3}$	$P_{1\text{-}12}$、$P_{1\text{-}30}$、$P_{1\text{-}4}$、$P_{1\text{-}40}$、$P_{1\text{-}41}$、$P_{1\text{-}46}$、$P_{1\text{-}49}$、$P_{10\text{-}1}$、$P_{10\text{-}12}$、$P_{10\text{-}16}$、$P_{10\text{-}17}$、$P_{10\text{-}20}$、$P_{10\text{-}22}$、$P_{10\text{-}24}$、$P_{10\text{-}26}$、 …… 、$P_{32\text{-}2}$、$P_{32\text{-}3}$、$P_{32\text{-}4}$、$P_{33\text{-}3}$、$P_{34\text{-}10}$、$P_{34\text{-}14}$、$P_{34\text{-}2}$、$P_{34\text{-}3}$、$P_{34\text{-}5}$、$P_{35\text{-}1}$、
$P_{I\text{-}B1}$	$P_{11\text{-}3}$、$P_{11\text{-}5}$、$P_{13\text{-}11}$、$P_{16\text{-}11}$、$P_{17\text{-}17}$、$P_{18\text{-}20}$、$P_{22\text{-}16}$、$P_{23\text{-}30}$、$P_{23\text{-}35}$、$P_{26\text{-}10}$、$P_{28\text{-}16}$、$P_{28\text{-}9}$、$P_{31\text{-}16}$、$P_{31\text{-}5}$、$P_{33\text{-}2}$、$P_{36\text{-}2}$、$P_{37\text{-}1}$、$P_{37\text{-}2}$、$P_{38\text{-}6}$、$P_{38\text{-}16}$、 …… 、$P_{40\text{-}16}$、$P_{40\text{-}17}$、$P_{34\text{-}6}$、$P_{34\text{-}9}$
$P_{I\text{-}B2}$	$P_{1\text{-}28}$、$P_{1\text{-}29}$、$P_{1\text{-}31}$、$P_{1\text{-}43}$、$P_{1\text{-}50}$、$P_{10\text{-}38}$、$P_{10\text{-}47}$、$P_{12\text{-}15}$、$P_{13\text{-}12}$、$P_{13\text{-}13}$、$P_{13\text{-}16}$、$P_{13\text{-}20}$、$P_{13\text{-}23}$、$P_{14\text{-}49}$、$P_{15\text{-}1}$、$P_{2\text{-}5}$、$P_{21\text{-}14}$、 …… 、$P_{30\text{-}10}$、$P_{31\text{-}15}$、$P_{31\text{-}18}$
$P_{I\text{-}B3}$	$P_{11\text{-}4}$、$P_{13\text{-}25}$、$P_{13\text{-}8}$、$P_{14\text{-}3}$、$P_{14\text{-}30}$、$P_{14\text{-}36}$、$P_{22\text{-}27}$、$P_{23\text{-}15}$、$P_{23\text{-}28}$、$P_{24\text{-}24}$
$P_{I\text{-}C1}$	$P_{1\text{-}1}$、$P_{1\text{-}10}$、$P_{1\text{-}14}$、$P_{1\text{-}16}$、$P_{1\text{-}17}$、$P_{1\text{-}18}$、$P_{1\text{-}19}$、$P_{1\text{-}2}$、$P_{1\text{-}20}$、$P_{1\text{-}21}$、$P_{1\text{-}23}$、$P_{1\text{-}24}$、$P_{1\text{-}25}$、$P_{1\text{-}26}$、$P_{1\text{-}3}$、$P_{1\text{-}33}$、 …… 、$P_{31\text{-}14}$、$P_{31\text{-}17}$、$P_{31\text{-}6}$、$P_{31\text{-}7}$、$P_{32\text{-}11}$、$P_{32\text{-}8}$、$P_{34\text{-}4}$、$P_{34\text{-}8}$、$P_{34\text{-}12}$、$P_{34\text{-}17}$
$P_{I\text{-}C2}$	$P_{10\text{-}23}$、$P_{17\text{-}13}$、$P_{17\text{-}20}$、$P_{18\text{-}11}$、$P_{21\text{-}21}$、$P_{24\text{-}43}$、$P_{24\text{-}8}$、$P_{27\text{-}22}$、$P_{29\text{-}8}$、$P_{34\text{-}18}$
$P_{I\text{-}C3}$	$P_{1\text{-}51}$、$P_{1\text{-}55}$、$P_{10\text{-}3}$、$P_{10\text{-}31}$、$P_{10\text{-}34}$、$P_{10\text{-}37}$、$P_{13\text{-}26}$、$P_{14\text{-}24}$、$P_{14\text{-}25}$、$P_{14\text{-}26}$、$P_{14\text{-}32}$、$P_{14\text{-}34}$、$P_{14\text{-}35}$、$P_{14\text{-}38}$、$P_{14\text{-}44}$、 …… 、$P_{26\text{-}1}$、$P_{26\text{-}15}$

sample cities selected for this study are the regional economic and population centers of China. Most of these cities are provincial capitals with high political status, and their low-carbon practices are representative of their provinces [2]. Therefore, the selection of LCC policies from these 35 cities can reflect the performance of LCC practices in China; and the improvement of LCC performance in these cities can also lead to the improvement of LCC performance nationwide.

3.2.2. Data collection

A total of 608 policy analysis units were retrieved according to the keyword of "Low-carbon" with the reference to the Peking University Law Database (PKUAW), which is the biggest law database in China, and the official website of the National Development and Reform Commission (NDRC) in each city for the period of 2006–2020. The collected documents are then coded according to the order of the sample cities, for example, "$P_{1\text{-}1}$" represents the first policy analysis unit in the first city Beijing. Given the large volume of data, the policy analysis units and their codes are shown in Appendix A.

4. Results and analysis

Using the research methodology developed in Section 3, the following results were obtained.

4.1. Identification of policy instruments for practicing LCC

Based on the policy analysis framework presented in section 3.1, this study identified policy instruments for the policy analysis units (see supplementary data), and some of the identification results are shown in Table 4.

4.2. Temporal evolution of LCC policy instruments in China

Based on the policy instruments in Table 4, the number of policy instruments in each year can be obtained which can reflect the temporal evolution of these policy instruments (as shown in Appendix B and Fig. 2).

As shown in Fig. 2, the authority instrument ($P_{I\text{-}A3}$) which emerged in 2007 was the earliest policy instrument for Chinese cities. Authority instruments ($P_{I\text{-}A3}$) and Information and advocacy instruments ($P_{I\text{-}C1}$) were the main policy instruments during most of the study period. Specifically, the authority instrument was the dominating policy instrument ($P_{I\text{-}A3}$) in 2010–2011 and 2014, and the information and advocacy instruments ($P_{I\text{-}c1}$) were the most commonly used policy instruments for 2012–2013 and 2015–2020. The proportion of Incentive instruments ($P_{I\text{-}B1}$) is the lowest during the whole study period, and there has been a lack of such policy instruments for several years.

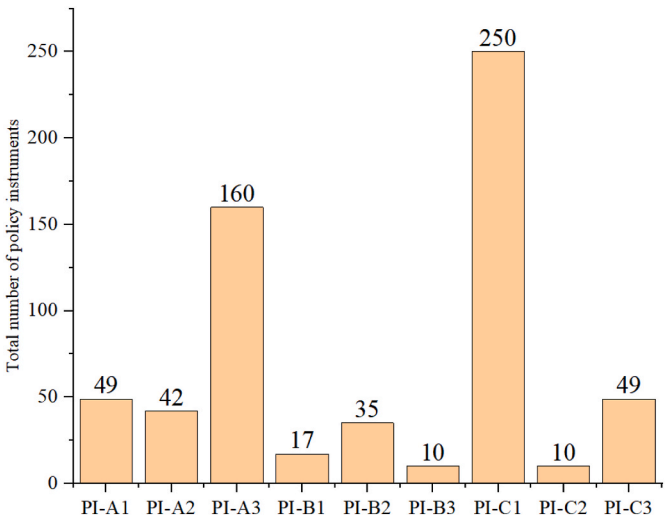

Fig. 3. The total number of policy instruments for the period of 2006–2020.

Based on the policy instruments in Appendix B, the total number of each policy instrument for the period of 2006–2020 can be obtained, which reflects the dimensional distribution of different types of policy instruments in China (as shown in Fig. 3).

As shown in Fig. 3, the top two policy instruments are 250 information and advocacy instruments ($P_{I\text{-}C1}$) and 160 authority instruments ($P_{I\text{-}A3}$). The number of policy instruments in the market instrument ($P_{I\text{-}B3}$) and incentive instrument ($P_{I\text{-}C2}$) is only 10. Notably, there is a lack of

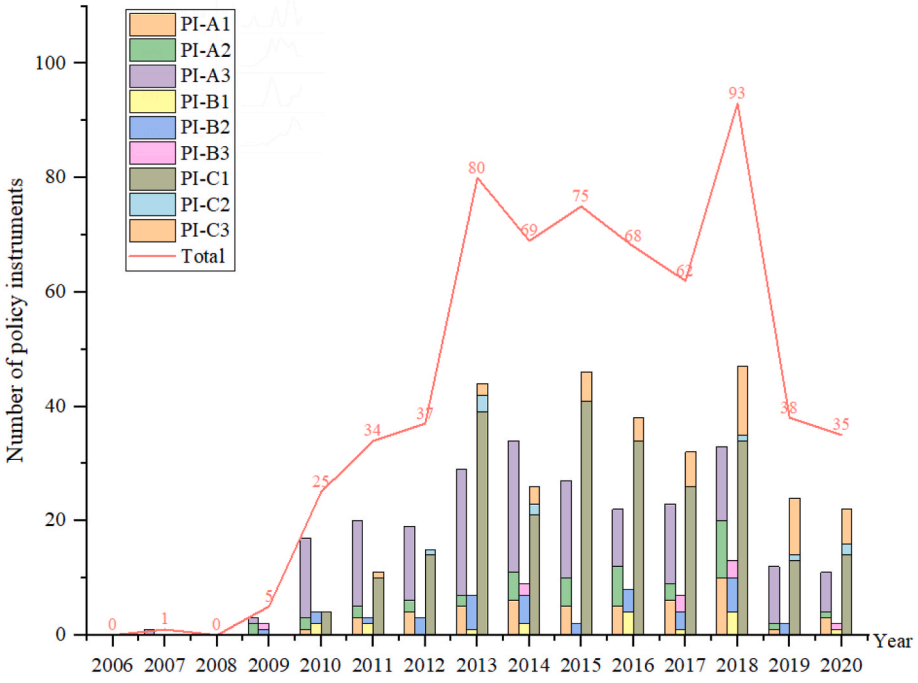

Fig. 2. Temporal evolution of LCC policy instruments in China.

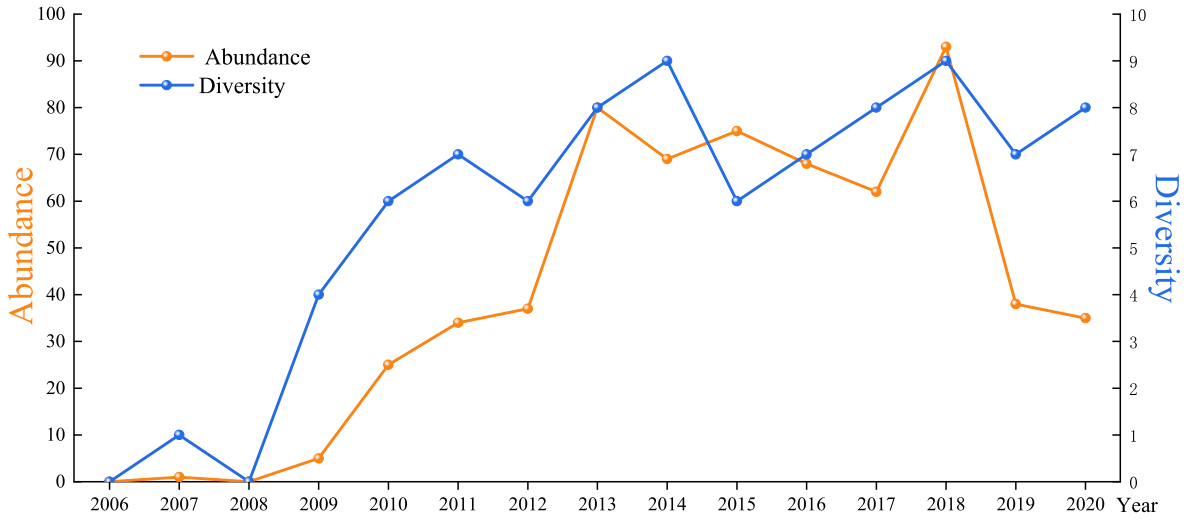

Fig. 4. Abundance and diversity of LCC policy instruments.

hybrid instruments ($P_{I\text{-}B}$), namely, the personal home and the community instruments ($P_{I\text{-}B1}$), the voluntary organization and the service instruments ($P_{I\text{-}B2}$) and the marketing instruments ($P_{I\text{-}B3}$).

To further demonstrate the evolution of LCC policy instruments in China, the number and types of policy instruments during the study period were counted, as shown in Fig. 4.

As shown in Fig. 4, the number of LCC policy instruments in China grew rapidly from 2006 to 2013, fluctuating from 2013 to 2018, dropping sharply from 93 in 2018 to 35 in 2020. It should be noted that the number of policy instruments at the city level in China was just 35 for the year 2020 even driven by the dual carbon target. Therefore, the Chinese government needs to increase the supply of policy instruments at the city level. In terms of the types of policy instruments, the types of policy instruments in China increased from one in 2007 to nine in 2014, and the types of policy instruments continue to improve.

4.3. Spatial differences of LCC policy instruments in China

According to the policy instruments in Appendix B, the number of policy instruments per city can be obtained, which can reflect the spatial variation of policy instruments in China (as shown in Appendix C). As shown in Appendix C, the information and advocacy instrument ($P_{I\text{-}c1}$) is the main policy instrument for most prior sample cities in China, such as Beijing, Hefei, Jinan, Qingdao, Zhengzhou, Wuhan, Changsha, Guangzhou, Nanning, Chongqing, Kunming, Guiyang, and so on. Some cities rely mainly on authoritative instruments ($P_{I\text{-}A3}$), such as Shijiazhuang, Harbin, Shanghai, Ningbo, Xi'an, Lanzhou and Yinchuan. The subsidies instruments ($P_{I\text{-}C3}$) are the domination policy instruments of Shenzhen.

Table 5
The number and types of LCC policy instruments in the sample cities.

City	A	D	City	A	D	City	A	D
Beijing	52	6	Qingdao	18	3	Chengdu	15	3
Shanghai	48	7	Tianjin	10	3	Xining	3	1
Ningbo	27	7	Shijiazhuang	8	3	Yinchuan	15	4
Hefei	46	7	Taiyuan	0	0	Urumqi	1	1
Nanchang	22	7	Hohhot	0	0	Nanjing	7	5
Changsha	31	8	Shenyang	4	2	Jinan	15	6
Guangzhou	33	7	Dalian	2	2	Haikou	16	5
Shenzhen	72	7	Changchun	6	2	Guiyang	18	5
Nanning	20	5	Harbin	13	3	Kunming	16	5
Chongqing	20	5	Fuzhou	5	4	Lanzhou	9	5
Xi 'an	18	5	Xiamen	13	4	Wuhan	14	5
Hangzhou	18	4	Zhengzhou	7	2			

To further demonstrate the evolution of LCC policy instruments in China, the abundance and diversity degree of policy instruments across cities can be obtained, as shown in Table 5.

The abundance of policy instruments can be reflected by the number of policy instruments. The high-ranking cities are Shenzhen, Beijing, Shanghai, Hefei, Guangzhou, Changsha, Ningbo, Nanchang, Chongqing and Nanning. The number of policy instruments in these cities was 73, 52, 48, 46, 33, 32, 27, 22, 21, and 20, respectively. The diversity of policy instruments can be reflected by the types of policy instruments. The high-ranking cities in terms of policy instruments are Changsha, Shenzhen, Shanghai, Hefei, Guangzhou, Ningbo, Nanjing, Beijing and Jinan. From a two-dimensional perspective of the number and type of policy instruments, the sample cities can be classified into four categories based on the Boston matrix, namely, Category I, Category II, Category III, and Category IV (as shown in Fig. 5).

As shown in Fig. 5, typical problems existing in LCC practice in different Chinese cities can be identified. Both the number and types of policy instruments in Beijing, Shanghai, Ningbo, Hefei, Nanchang, Changsha, Guangzhou, Shenzhen, Chongqing, and Xi'an are relatively high. Category II cities, namely, Hangzhou and Qingdao, suffer from overly homogeneous policy instruments type. Category III cities, which included Tianjin, Shijiazhuang, Taiyuan, Hohhot, Shenyang, Dalian, Changchun, Harbin, Fuzhou, Xiamen, Zhengzhou, Chengdu, Xining, Yinchuan, and Urumqi, are insufficient both in the number and type of policy instruments. While cities in Category IV, including Nanjing, Jinan, Haikou, Kunming, Lanzhou and Wuhan, have a wide range of policy instrument types, while the number of policy instruments in these cities is relatively small.

5. Discussion

5.1. Experience and lessons from temporal evolution analysis

The temporal evolution of the LCC policy instruments demonstrates that the amount of information and advocacy instruments ($P_{I\text{-}C1}$) in China is the most during the study period. The main measures adopted by Chinese Cities for $P_{I\text{-}C1}$ are "Energy Conservation and Emission Reduction publicity and Education". However, OECD [54] and Blackman et al. [55] pointed out that the information and advocacy instruments ($P_{I\text{-}C1}$) have the lowest degree of mandatory governance, and are not as effective as $P_{I\text{-}A}$ and $P_{I\text{-}B}$. Therefore, the Chinese government should not rely heavily on information and advocacy instruments ($P_{I\text{-}C1}$).

In terms of the overall distribution of LCC policy instruments, China lacks three types of Hybrid instruments ($P_{I\text{-}B}$). The lack of personal

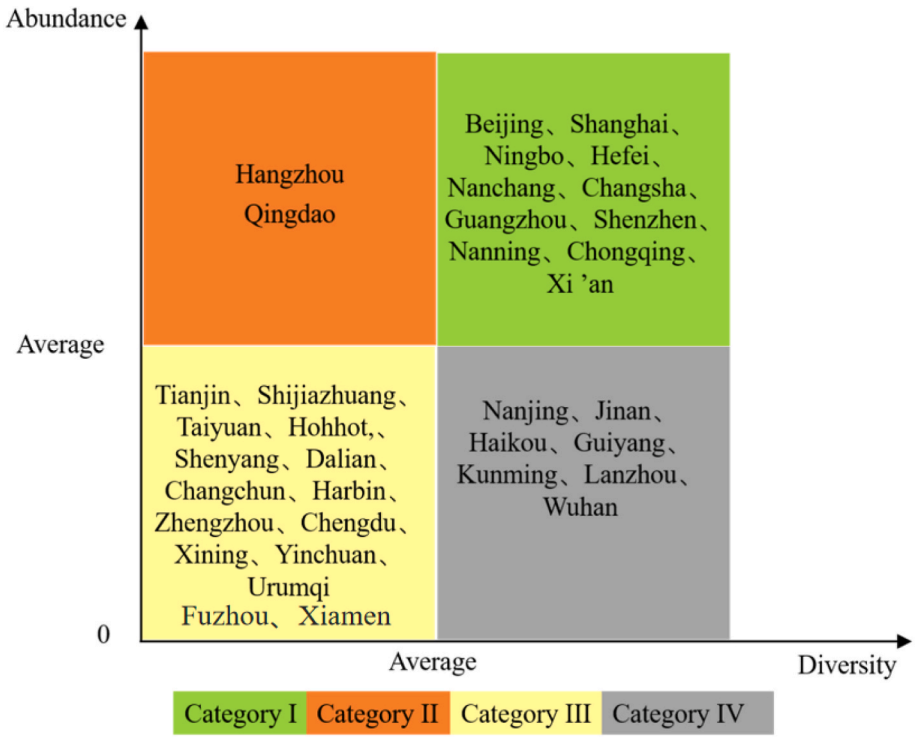

Fig. 5. Classification result of the policy instruments in sample cities.

household and community instruments ($P_{I\text{-}B1}$) suggests that LCC practice in China is mostly top-down commands and a lack of bottom-up spontaneous actions. The C40 cities constitute an international alliance of cities that exemplify low-carbon city practices, demonstrating a steadfast commitment to reducing greenhouse gas emissions and mitigating climate risks [56]. Based on the experience of LCC practices in C40 cities, it can be observed that C40 cities are more focused on the "personal household" and "communities" practices. For example, Los Angeles has released the *2020 Los Angeles Community Climate Action Plan*, and Austin has launched the *Austin Community Climate Plan*. It is recommended that China's LCC practice should take full advantage of the role of individuals and families. From an individual perspective, carbon emission measurement software should be rolled out at the individual level; from a household perspective, an atmosphere of joint energy-saving and emission reduction should be formed and good habits can be developed, such as turning off lights when going out.

The voluntary organizations and service tools ($P_{I\text{-}B2}$) emphasized the importance of voluntary organizations, especially Non-Government Organizations (NGOs), in practicing LCC. However, existing LCC policies in Chinese cities neglect the importance of voluntary organizations. A study by Luo et al.[25] shows that most of the existing energy conservation and emission reduction measures in China are promoted by the government, the resources and influence of NGOs are underdeveloped, and the lack of positive practice of NGOs significantly reduces the effectiveness of LCC implementation.

The lack of market instruments ($P_{I\text{-}B3}$) in China suggests that the market should be involved in LCC practice. In fact, the international LCC practice attaches more importance to the use of market instruments. For example, according to the *Tokyo Climate Change Strategy: Progress and Future Prospects* [57], Japan has adapted market instruments to local conditions, implementing carbon trading schemes for large-scale engineering facilities, and carbon emission systems for small and medium-sized facilities.

5.2. *Experience and lessons from spatial differences analysis*

According to the results of the analysis of section 4.3, Shenzhen has developed a more comprehensive system of policy instruments that can serve as a reference for other cities in China. From the perspective of mandatory instruments ($P_{I\text{-}A}$), Shenzhen has introduced the "Medium and Long Term Plan for Low-Carbon Development in Shenzhen", and released guidelines for low-carbon evaluation of spots, hotels, enterprises, shopping malls and communities. From the perspective of hybrid instruments ($P_{I\text{-}B}$), Shenzhen has made full use of individual household and community instruments to establish the carbon inclusion system, exploit market instruments and set up the carbon trading system. In terms of voluntary instruments ($P_{I\text{-}C}$), the most notable feature of Shenzhen is the use of multiple subsidy instruments ($P_{I\text{-}C3}$) to guide market adjustments through various incentives and subsidies for emerging industries and modern service industries. Another interesting finding of the spatial different analysis is that cities with different levels of economic development have diverse preferences in the adoption of policy instruments. Specifically, cities with better economic backgrounds use more information and advocacy instruments ($P_{I\text{-}C3}$), while cities with poor economic conditions prefer to use authoritative instruments ($P_{I\text{-}A3}$). This finding is consistent with previous research. According to Huang et al. [45], policy implements in developed regions are more inclined to use economic incentive policy instruments than in developing regions.

An analysis of the abundance and diversity of LCC policy instruments in China reveals that the performance of low-carbon policy instruments in the sample is not positively correlated with their participation in low-carbon pilot city projects. Cities with better performance in Category I include LCC pilot cities, such as Beijing, Shanghai, Guangzhou, Shenzhen, and Nanchang, and also have cities which have not taken part in LCC pilot programs, such as Hefei and Xi'an. Tianjin and Xiamen, which are the batch of first pilot cities, ranked Category III. It further suggests that the LCC pilot cities did not play a demonstration role in the implementation of the policy instruments. This is contrary to the existing study by Shen et al. [3], which states that low-carbon pilot projects

can replicate LCC practices across the country. In fact, low-carbon pilot cities do not have any economic and legislative priorities in LCC practices [9,58]. Therefore, this study concludes that the better performance of low-carbon pilot cities is not due to the implementation of additional policy instruments. It is recommended that more emphasis should be placed on the leadership and demonstration role of pilot cities when implementing policy instruments under the dual carbon target.

5.3. Policy implications

Based on the experiences and lessons discussed in the previous section, a number of policy implications are proposed as follows.

5.3.1. Increase the number of policy instruments for practicing LCC

From the evolution analysis of the abundance and diversity of LCC policy instruments, the number of LCC policy instruments in the sample cities is only 35, and the supply of LCC policies in China is insufficient. This lack of LCC policy instruments suggests that there is a need necessary to further strengthen the regulations of LCC implementation in China. In fact, driven by the dual carbon goals of "Carbon Peak 2030" and "Carbon Neutral 2060", LCC practices should receive more attention from the Chinese government and more regulatory policy instruments should be promoted in the near future.

5.3.2. Improving the performance of poor policy instruments

According to the analysis of policy instruments for practicing LCC in China, there is a lack of individual, family and community instruments ($P_{I\text{-}B1}$), voluntary organization and service tools ($P_{I\text{-}B2}$) and market instruments ($P_{I\text{-}B3}$) in China. Drawing on international experience, the following strategies are proposed for practicing LCC.

As for individual, family, and community instruments ($P_{I\text{-}B1}$), concerted efforts across multiple levels of individuals, families, and communities should be paid. At the individual level, it is imperative to enhance low-carbon awareness and embrace low-carbon behaviors in daily life such as utilizing public transportation. Furthermore, it is crucial to establish eco-friendly households where family members collectively engage in a low-carbon lifestyle. For example, implementation of household waste segregation ensures recyclables are treated as valuable resources. In addition, promoting the transformation of communities towards sustainability by enhancing energy efficiency and minimizing carbon emissions through initiatives like constructing solar power facilities and advocating for energy-saving buildings.

The implementation of voluntary organizations and service policy tools ($P_{I\text{-}B2}$) stands as a pivotal strategy for LCC practice. Firstly, it is crucial to establish low-carbon volunteer organizations to encourage public engagement in low-carbon actions. Secondly, the government should guide and incentivize enterprises and institutions to provide various low-carbon services such as eco-friendly travel options, green energy consulting services, carbon footprint calculations, etc. Last but not least, the government can facilitate collaboration and information sharing by establishing a platform that enables different voluntary organizations and service agencies to cooperate with each other, exchange experiences, and share resources.

Establish a market-oriented policy instrument ($P_{I\text{-}B3}$) to guide and incentivize active participation of all sectors in low-carbon action: (1) Establish a unified national carbon emission trading market, enabling enterprises to engage in buying and selling carbon emission rights; (2) Encourage financial institutions to develop green financial products, such as green bonds and green funds, for providing financing support to low-carbon projects; (3) The government should formulate green procurement policies that prioritize the acquisition of products and services meeting low-carbon standards.

5.3.3. Designing tailor-made policy instruments

Cites of different categories in Fig. 5 will have different strategies for practicing LCC. Specifically, category I cities perform better in terms of abundance and diversity of policy instruments, and they can be used as experience cities to share their experience with other cities. Category II cities are higher in abundance and lower in diversity, indicating that they have more repetitive policy instruments, and they need to increase the variety of policy instruments. For example, the second batch of low carbon pilot cities, Hangzhou and Qingdao, face the problem of a single type of policy instrument, and the diversity of policy instruments should be increased. Category III cities have poor performance both in abundance and diversity and need to improve the performance of policy instruments in these two areas. Cities in Category IV have low abundance but poor diversity, which can increase the number of policy instruments based on existing types of policy instruments.

6. Conclusions

Policy instruments are important instruments to guide low carbon city practice. Most existing studies failed to analyze the overall performance of LCC policy instruments in China. This study identifies the strengths and weaknesses of China's LCC policy instrument by analyzing temporal and spatial evolution and then proposes tailored policy implications by learning experience from best practices.

The temporal evolution of LCC policy instruments evidences the following three interesting findings. China had the highest number of information and advocacy instruments ($P_{I\text{-}C1}$) during the study period. China lacks three types of hybrid instruments ($P_{I\text{-}B}$) in China. Based on the results of the analysis of spatial differences, there are three main findings. Firstly, Shenzhen has formed a more comprehensive system of policy instruments which can provide a reference for other cities in China. Secondly, cities at different levels of economic development have a diversity priority in terms of adopting policy instruments. Finally, the LCC pilot cities did not play a demonstration role in policy instrument implementation.

The significance of this study can be highlighted as follows. (1) This study theoretically introduces the policy instrument framework for analyzing the performance of low city policies, providing a new analytical perspective for the LCC discipline. (2) Practically, this study provides a spatial-temporal analysis of policy instruments in China, which provides an important reference for governors to develop targeted low carbon policies. The limitations of this study are the following: LCC policy documents have been collected from 35 sample cities, and more case cities could have been selected. The paper primarily focuses on descriptive statistics, while lacking an in-depth analysis of the experiences and lessons learned from pilot cities. Future studies can incorporate comprehensive analysis and discussion of the insights gained from low-carbon pilots to present their value more comprehensively. This study relied solely on the number and variety of policy instruments as measures of abundance and diversity, and multiple aspects of policy instruments for a more comprehensive evaluation can be explored. In addition, the scenario analysis method could have been used to demonstrate the effectiveness of various policy instruments.

CRediT authorship contribution statement

Bei He: Conceptualization, Writing – original draft, Methodology. **Zhijie Li:** Data curation, Methodology, Writing – review & editing, Visualization. **Xiaoyun Du:** Conceptualization, Supervision, Project administration, Funding acquisition. **Xiaoxuan Wei:** Data curation, Software. **Jiayu Li:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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