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Advancements, challenges and prospects

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Incentive initiatives on energy-efficient renovation of existing buildings towards carbon–neutral blueprints in China: Advancements, challenges and prospects

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ABSTRACT

Under China's national strategy of carbon neutrality by 2060, it is urgently necessary and challenging for the governments to proactively explore policy tools to facilitate energy-efficient renovation of existing buildings. Currently, a considerable number of studies have been conducted on building energy-efficient renovation and its derivative topics, however, a comprehensive overview on incentive initiatives related to existing renovation practices in China is still scarce, such as a lack of critical correlation analysis between national and local initiatives, a lack of the synthesis and critique towards the latest policies and related achievements, and inadequate generalization of the diverse and multi-layered barriers and challenges in building energy-efficient renovation practices. To address these issues, this paper adopts a diversified policy segmentation approach to deeply analyze the dynamic evolution of the incentive initiatives from both national and local level perspectives, as well as to establish the related network of policy linkages between national to local, and between different localities. In addition, this paper presents a critical analysis on representative initiatives in two batches of pilot cities, and proposes good practices and valuable experiences for building energy-efficient renovation. Finally, this paper further summarizes and discusses the barriers to building energy-efficient renovation from four perspectives: governments, householders, enterprises and research institutions, and proposes a series of targeted and feasible pathways and strategies. This study can provide theoretical guidance and targeted recommendations for the formulation of policies, standards and regulations for building energy-efficient renovation in China.

1. Introduction

A series of environmental issues arising from energy production and consumption, such as climate warming, environmental pollution and increased extreme weather, have aroused considerable worldwide concerns [1,2]. Meanwhile, as the world's second-largest economy, China ranks first in energy consumption and carbon emissions around the world [3,4]. The total energy consumption in 2021 has already reached 5.24 billion tons of standard coal [5], thus China's decarburization actions will have a widespread and long-lasting impact on the world. To achieve the global climate-related targets mentioned in the Paris Agreement [6], in September 2020, Chinese President Xi Jinping announced that China's national strategy aims to achieve carbon neutrality by 2060. This means that by 2060, China aims to balance its CO_2 emissions with measures that remove or offset an equivalent amount of CO_2 from the atmosphere [7]. According to the China Association of Building Energy Efficiency (CABEE), the energy consumption of China's buildings throughout their life cycle accounts for 46.5% of the country's total energy consumption and 51.2% of carbon emissions in 2018 [8]. Therefore, as a major contributor to greenhouse gas emissions, the decarburization of the building sector has become a priority for sustainable development in China as well as worldwide [9,10].

In the context of global warming and environmental degradation, authorities have identified improving the energy efficiency of existing commercial and residential buildings as a priority in national building decarburization policies [11]. China is also contributing to the global struggle against climate changes with practical actions [12]. However,

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Nomenclature

BIM	Building Information Modeling
CABEE	China Association of Building Energy Efficiency
CCRT	China Central Radio and Television
DB	Design-Build
DBB	Design-Bid-Build
FYP	Five-Year Plans
GDP	Gross domestic product
MOHURD	Ministry of Housing and Urban-Rural Development

China has been facing prominent issues such as large building stock and high energy consumption [13,14]. In addition, existing buildings account for the largest proportion of the total building inventory, but less than 10% of them can be rated as energy efficient [15]. This is because most existing buildings (based on the Energy Conservation Design Standards for Residential Buildings (JGJ26-1986) [16]) have not prominently considered energy efficiency during their construction stages, and are unable to match the current standards, resulting in substantial energy consumption due to their inadequate energy performance. However, many non-energy efficient buildings still require service for more than 30 years or even longer, so energy renovation (i.e., reducing building energy consumption by changing the physical characteristics of existing buildings or replacing energy-consuming equipment [17]) has been considered an effective measure to overcome these challenges. Over the years, China has consistently developed and implemented top-down energy efficiency measures [18], but most of these laws and regulations have mainly targeted new buildings [15]. In order to steadily improve the energy efficiency of buildings, it is necessary to improve the policy and regulatory framework for building energy-efficient renovation in China. Overall, China's existing buildings have tremendous untapped potentials for energy efficiency and decarburization, and exploring the incentive initiatives for retrofitting existing buildings can effectively contribute to the country's strategic goal of carbon neutrality.

At present, the studies related to building energy-efficient renovation policies or measures have achieved some milestones: i) In terms of legal standards and evaluation of building energy-efficient renovation, Zhang et al. [19] compiled and compared energy-efficient renovation policy tools in 11 countries, analyzed barriers from the perspectives of awareness and information, technology, finance, and management, and made rationalized policy recommendations based on the holistic process of successful implementation of renovation programs. Ho et al. [20] adopted the systematic literature review and focus group sessions to select key performance indicators such as payback period to further develop a performance assessment system for commercial building renovation; ii) In terms of incentives for building energy-efficient renovation, Amoruso et al. [21] analyzed the weaknesses of current regulations in Korea to support building energy-efficient renovation through exemplary scenarios corresponding to typical building types, and further quantified the calculation methods and criteria for financial incentives regarding building height, area, and energy efficiency technologies. Tajani et al. [22] assessed the impacts of existing financial incentives for energy-efficient renovation of buildings in Italy on the economic benefits for the operators involved by creating Geographical Maps of Economic Benefits and Convenience Maps, and estimated the minimum subsidies for investors under different climatic conditions and building technologies; iii) In terms of owner/enterprise participation in building energy-efficient renovation, Ma et al. [23] derived three main elements for homeowner participation in the processes of building energy-efficient renovation through semi-structured interviews and questionnaires, including the procedures, the composition of the working group, and the discussed contents, and suggested the establishment of a homeowners' association to be a communication channel between homeowners and the working group. Wade et al. [24] conducted an investigation based on interview data from partner firms for building energy-efficient renovation and suggested that policy makers developed shared databases to guide the allocation of resources and responsibilities between local governments and delivery enterprises.

In addition, many researchers have systematically summarized and analyzed how to effectively promote energy-efficient renovation in existing buildings, and have proposed scientific and reasonable development paths and implementation strategies. Table 1 lists the review literature related to building energy renovation in recent years. Their research topics mainly include the following three categories: 1) Building energy renovation related policies. These articles cover building energy renovation policies in the United Kingdom, the United States, Canada, and China, and mostly provide comprehensive reviews from the characteristics, development process, barriers and challenges, and influencing factors of these policies; 2) Research trends in building energy renovation. These articles use scientific statistical mapping techniques to explore the links between authors, countries, journals, and keywords in the literature related to building energy renovation; 3) Technologies related to building energy retrofits. These articles summarize the application and optimization of technologies such as decision-making models, software tools, and optimization methods in the field of building energy renovation.

By integrating the literature on policy studies of energy-efficient renovation for existing buildings in recent years, a large number of researchers have explored and summarized the application and development of building energy renovation policies from different perspectives, such as policy evolution history and policy barrier analysis. However, there are still some significant research gaps in the existing studies, mainly including the following aspects: (1) Local political measures and instruments are often overlooked in existing studies. There is a lack of detailed studies on the correlation between national and local policies, especially on the differences between existing building renovation policies in representative provinces of different climate zones and the comparison of important implications; (2) Existing studies lack an up-to-date summarization of the implementation measures and advancements of the second batch of pilot projects; (3) Few studies focus on the summarization of implementation barriers that weaken the scientificity, continuity and targeting of policy initiatives from the different stakeholders. Meanwhile, the available studies have not yet given a comprehensive blueprint framework of targeted implementation pathways and development recommendations.

The above-mentioned research gaps in the existing literature need to be studied, so it is necessary to conduct a comprehensive overview and critical analysis of the incentive initiatives on energy-efficient renovation of existing buildings towards carbon–neutral blueprints. This paper will be organized as follows: Section 2 presents the research methodology, including research methods and scopes; Section 3 provides a statistical overview of the current research status for energy-efficient renovations; Section 4 summarizes and compares the existing policy initiatives of building energy-efficient renovation from the national and local governments; Section 5 analyzes and discusses the policy polit initiatives; Section 6 systematically analyzes the barriers and challenges in the implementation of energy efficiency policies, and Section 7 summarizes the targeted implementation pathways and development recommendations. Section 8 presents the conclusions and future studies. This study aims to provide theoretical guidance and targeted recommendations for the formulation of policies, standards and regulations for building energy-efficient renovation in China.

2. Methodology

The research methods in this study are divided into two main categories, one is the literature review and another is the summarization of policy-oriented documents. The literature search method is mainly

Table 1
Recent review papers related to energy-efficient renovation of existing buildings.

Year	Authors	Research method	Main contents
2022	Alabid et al. [25]	Statistical Analysis & Policy Review	This paper reviewed the building renovation policies adopted following the UK's commitment to reduce carbon emissions and used secondary research methods to analyze scientific research data from journals and building renovation reports.
2022	Du et al. [26]	Policy Review	This paper provided a systematic review of the literature on the decision-making process, drivers, and barriers to building energy renovation policies.
2022	Tetteh et al. [27]	Statistical Analysis	This paper used scientometric mapping techniques to systematically quantify the existing research trends, research interests, and keyword clustering of green retrofits worldwide.
2022	Fořt et al. [28]	Literature Review	This paper comprehensively analyzed the studies related to the environmental impact, technical feasibility, economic viability and social acceptance of sustainable building renovation.
2021	He et al. [29]	Statistical Analysis & Literature Review	This paper used visualization methods to analyze the distribution network of contributing authors, countries, journals, keywords, and time-zones of literature related to energy renovation in buildings.
2021	Han et al. [18]	Policy Review	This paper described the development of China's building energy efficiency policies from 1980 to 2019 in a chronological manner, including policy achievements, purposes, innovations, and contents.
2021	Ibañez Iralde et al. [30]	Statistical & Policy Review	This paper classified and weighted building energy renovation measures in Spain to show the effectiveness of the distribution of dedicated funds and the development of programs at the regional and local levels.
2020	Economidou et al. [31]	Policy Review	This paper adopted a policy classification approach to collate policy instruments for improving energy efficiency of new and existing buildings in the EU over the last 50 years.
2020	Liu et al. [32]	Statistical & Policy Review	This paper listed the latest developments in China's renovation policies during 1996–2019 and explored the characteristics of each policy and the relationship between policies based on content analysis.
2020	Liu et al. [33]	Policy Review	This paper used a policy classification approach to organize policies for building energy-efficient renovation from both the world and China.
2020	Kerr et al. [34]	Policy Review	This paper conducted a systematic review of home energy renovation and analyzed policies such as subsidized loans considering additionality, positive spillover effects, and market effects.
2020	Hashempour et al. [35]	Statistical Analysis & Literature Review	This paper reviewed the energy performance optimization of existing buildings from the perspective of decision-making models, software tools, optimization methods, and geographic locations through case studies.
2020	Grillone et al. [36]	Literature Review	This paper thoroughly analyzed the technical studies of statistical learning models, machine learning models, for energy-efficient renovation of buildings, and identified research gaps.

based on the websites of ScienceDirect and Website of Science, which contain a large number of journal papers with widespread impacts. The retrieval process mainly uses the advanced search options of the above two platforms, such as, inputting a search query and selecting any paper found in the title, abstract and keywords. Two additional search restrictions are imposed, one that articles and conference papers are the only document types considered, and the other that the period covered is from 2010 to 2022 (this retrieval ends on November 30, 2022). The selected keywords are related to the topics of ("energy efficiency" OR "energy-efficient" OR "energy technology" OR "energy-saving") AND ("renovation" OR "retrofit" OR "renovate") OR ("energy efficient renovation ").

Under the thematic keywords, the keywords of existing energy-efficient renovation policies ("policy" OR "political" OR "measure") were entered to summarize the existing literature, and this paper divided the policies into six types of objectives, regulations, economy, knowledge, evaluation and organization, and professional training to complete Section 4. For national or local policies issued by the Chinese government, the research documents were searched for relevant information through official websites in addition to journal papers, where common official websites include the website of the Ministry of Housing and Urban-Rural Development of the People's Republic of China, the wesite of Chinese government, the website of National Development and Reform Commission of the People's Republic of China, and the official websites of the subordinate provinces and municipalities and regions. The key words of pilot projects ("pilot" OR "reform program" OR "trial" OR "demonstration") were selected, as well as the 11 pilot cities were searched individually to receive their results and progress achieved at the current stages to complete Section 5.

Under the theme keywords, the key words ("problem" OR "challenge" OR "limitation" OR "obstacle" OR "barrier") were supplemented with existing barriers to building energy-efficient renovation, and then an in-depth perusal through the publications and collections of barriers revealed that many barriers had similar connotations, such as "lack of technical expertise" and "lack of knowledge"; "lack of financial support" and "lack of financial incentives"; and "resistance to change" and "uncertainty about behavioral change." The above representations were rationalized and the retrieved barriers were finally identified into four categories: governmental barriers ("government" OR "political" OR "supervision"), residential occupant barriers ("housing" OR "housing" OR "residential" OR " domestic" OR "social" OR "public"), barriers to participation in businesses ("enterprise" OR "businesses" OR "residential"), and barriers to researchers ("researcher" OR "study"), and again search with the keywords corresponding to the barriers to complete Section 6. Based on the existing literature, strategies and pathways to overcome these barriers were proposed to complete Section 7.

3. Statistical overview of current status on energy-efficient renovations

This section used the CiteSpace, a Java-based literature visualization and analysis software, where the underlying data were obtained from the above qualified search conditions. The contents of this section are summarized and analyzed in terms of research topics and located countries. Clustering analysis was used to obtain the main research topics in the field of building energy-efficient renovation. A research development timeline of nine knowledge hotspots was constructed, as shown Fig. 1 in Fig. 2, which can be divided into two categories: technology and management. From the technical perspective, building "performance" reflects the functions that can be achieved in retrofitted buildings [37]. "Project" is closely linked to other research areas as validation tools and data bases. Technical "analysis" and "improvement" are certain methods to make retrofitted buildings further energy efficient. "Design" is targeted to different geographical and climatic conditions to increase building comfort [38]. "Model" is used to simulate and predicting building performance before and after retrofitting [39], with high frequency of keywords such as machine learning [40], neural networks in literature retrieval and consolidation. Geographic Information System (GIS) and other "surveillance" tools for extracting and processing environmental elements entered the academics around 2015. The technology-based research on building energy-efficient renovation above is the supporting tool to facilitate the decision-making of renovation. From the management perspective, the establishment of suitable indicator systems can be used to comprehensively assess and analyze the effectiveness of building energy-efficient renovation [41]. The importance of stakeholder participation, especially occupant participation, has been noticed by academics around 2012 and the number of related articles has further increased significantly after 2015. "Policies" play a role in encouraging occupant participation in building energy-efficient renovation and enterprises preferentially considering energy efficiency [42]. However, the number of articles distributed across the timeline of building energy renovation policy studies is relatively small in the overall context.

In summary, the research emphasis on building energy-efficient renovation has gradually shifted from technology (e.g., building performance simulation, project information extraction and analysis, and multi-objective optimal design, etc.) to management (e.g., implementation barriers, and driving forces, etc.), among which the decision-making of building energy-efficient renovation is a relatively unattractive field. However, it is noteworthy that there are thin lines between the topic vocabularies (i.e., a limited number of linked articles) as well as academic silos, which indicates that there is still insufficient academic communication and networking in the field of energy-efficient renovation for buildings.

Regarding the distribution of research related to building energy-efficient renovation in different countries, Fig. 3 shows the names of the countries that published more than 30 papers within the selected time nodes. In Fig. 3, larger nodes indicate more papers published on related topics, and lighter node colors indicate more recent publications, and the connecting lines of different nodes represent the correlation between the linked articles. Fig. 4 shows the top 10 countries in terms of the number of papers published on related topics and the corresponding number of published articles. It shows that scholars belonging to Italy have published the highest number of papers on the topic of energy-efficient renovation in buildings in the selected time interval. It should be noted that "Peoples R China" only refers to papers with Chinese affiliation. This data also indicates that Chinese scholars have not yet paid enough attention to research and practice related to building energy-efficient renovation.

4. Existing policy initiatives of building energy-efficient renovation

4.1. Existing policy initiatives from the national government

In recent years, Chinese government has formulated a series of favorable policies, laws and standards for energy-efficient renovation of existing buildings, such as assessment tools, certification standards and corresponding incentives. These have effectively provided guidance on the motivation and behavior of enterprises and occupants for the energy-

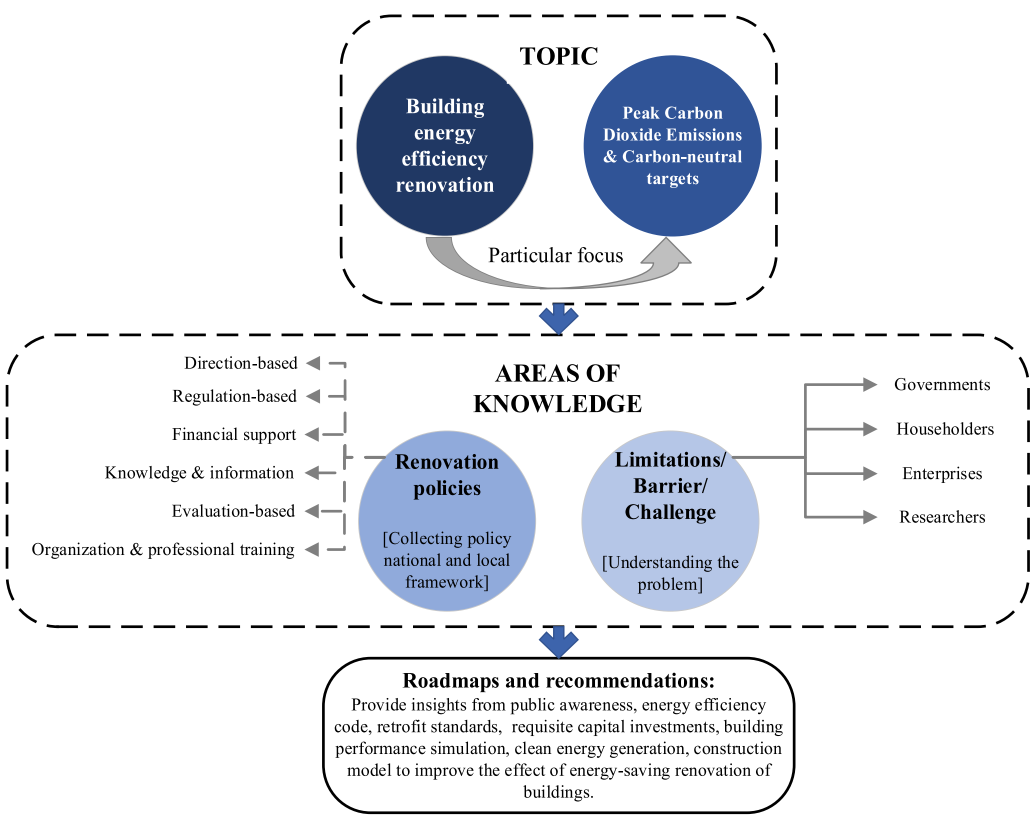

Fig. 1. Research methodology: areas of knowledge and covered topics.

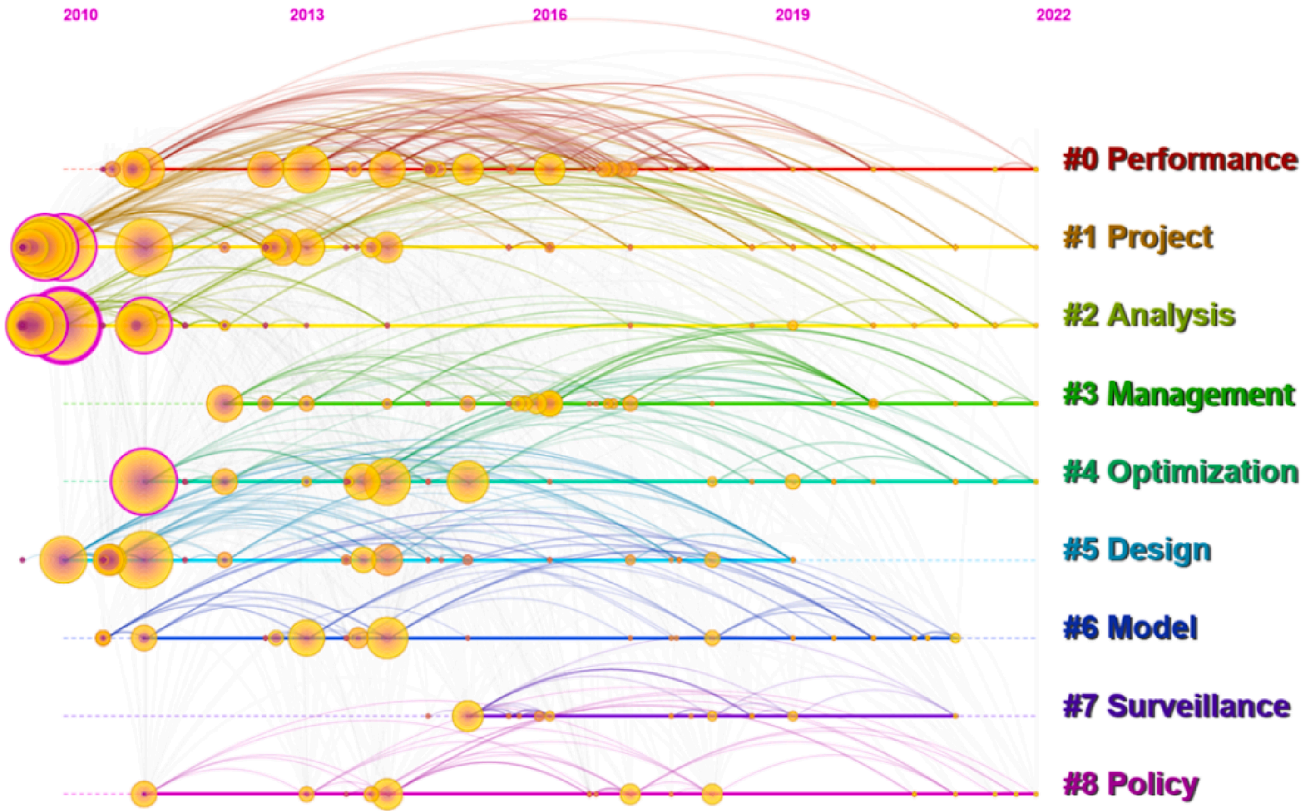

Fig. 2. Research development roadmap related to building energy-efficient renovation.

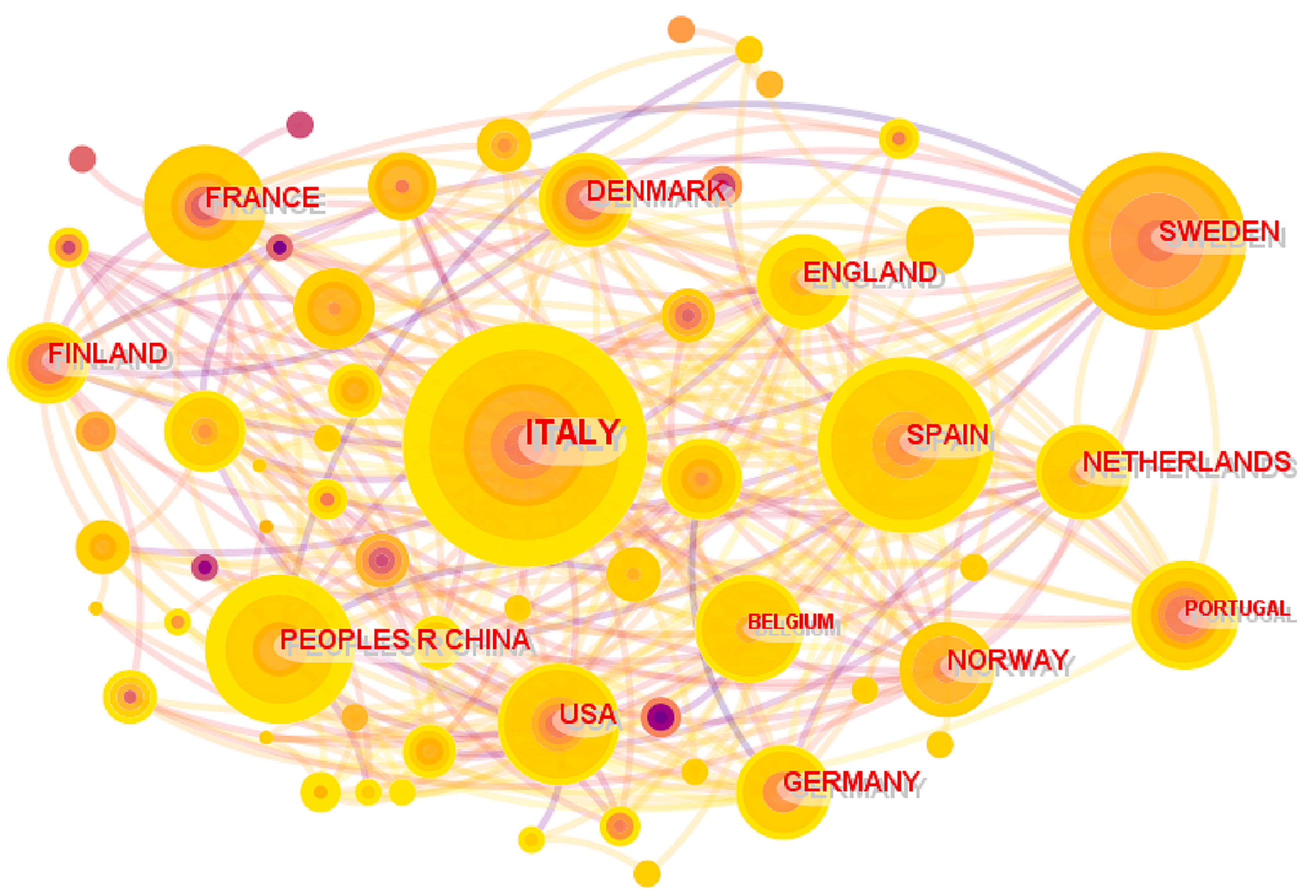

Fig. 3. Countries with published papers on the topic of building energy-efficient retrofit.

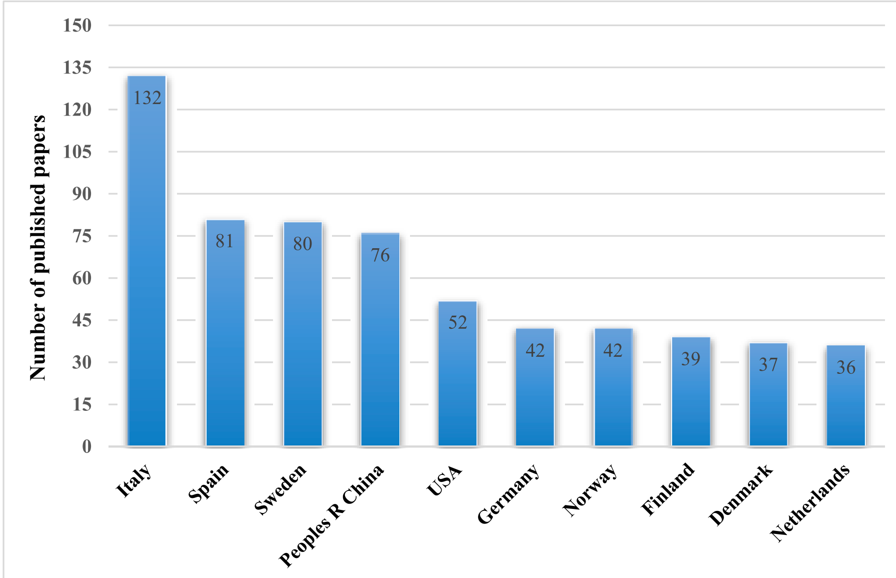

Fig. 4. The statistics of the top 10 countries in terms of the number of published papers.

efficient renovation of existing buildings, thereby promoting the improvement of building energy efficiency [33]. This section collects documents related to building energy-efficient renovation in China from relevant academic publications and government websites, and then categorizes and summarizes the six types of policies issued at the national level as shown in Fig. 5.

4.1.1. Direction-based policies

Improving building performance and achieving China's carbon neutrality goals through building energy-efficient renovation has been identified as a national development strategy that requires governments at all levels to develop appropriate medium- and long-term building energy-efficient plans that are regularly supplemented with short-term targets for their implementations, while incorporating them into annual plans and reporting on their progress. In recent years, the relevant national direction-based policies are summarized in Fig. 5 (a), and most typically is the four "Five-Year Plans (FYP)" after 2006 [64]. Under the background of energy contradictions and environmental issues, the guiding policies have proposed higher requirements for building energy retrofitting according to China's national scenarios, and gradually focused on the refinement of retrofitting measures and the quantification of targets, which mainly manifested in the expansion of retrofitted building areas and the improvement of energy efficiency [65].

These policies promote the sequential and successive development of the building industry by solving the prominent problems faced at each stage, thus facilitating the phased adjustment of regions and targets for building energy-efficient renovation in China, and providing forward-looking and systematic guidance for local policies and strategies. The 11th FYP focuses on the development of heavy industry, with less investment in the energy efficiency improvement of buildings. The 12th and 14th FYP prioritize the renovation of building energy efficiency and make the following changes: from energy-efficient buildings to green buildings, from single buildings to regional buildings, from "light green" (emphasizing localization and neglecting the overall) to "deep green" (emphasizing ecosystem interactions and dependencies). In the recent two years, the Chinese government has proposed new priorities for moving toward carbon neutrality, such as clean energy and new urbanization [7].

4.1.2. Regulation-based policies

Regulations play a key role in promoting and managing energy-efficient renovation of buildings, and as a legal-level normative document, they effectively guide and enforce the relevant authorities to rapidly adopt effective measures to improve building energy efficiency [66]. Some studies have shown that if some energy efficiency measures are not supported by corresponding regulations, it is difficult for the relevant authorities to form a speedy response to adopt effective actions, which leads to difficulties in achieving the desired goals for sustainable development transition [67]. The regulatory-type policies related to building energy-efficient renovation in China are summarized in Fig. 5 (b). Existing building energy efficiency regulations cover all stages, including design, construction, operation, monitoring and evaluation, and maintenance and retrofitting. These documents regulate the social relationships formed in building energy efficiency activities, and the subjects of legal relationships include construction contractors, supervision organizations, properties, and homeowners, while the clients of legal relationships are for decreasing building energy consumption [68].

With the transformation and upgrading of the building industry in recent years, these regulatory documents continuously improve the relevant provisions of renovation process so as to provide legal protection for building energy efficiency. However, at this stage, there is still a lack of overall implementation effectiveness of existing energy-efficient renovation, which is mainly due to the fact that the existing regulatory documents mainly focus on new buildings, including residential building energy efficiency, and public building energy efficiency, etc. However, there are relatively less mandatory regulations and policies related to building energy renovation, especially for the specific energy-efficient renovation measures. Therefore, it is necessary to further improve and strengthen the regulatory provisions related to energy-efficient renovation to improve the overall renovation rate.

4.1.3. Financial support policies

In 2011, the State Council of China issued a notification to stipulate that governments at all levels should arrange certain financial resources in their budgets to support the priority projects of energy conservation and carbon emission reduction, such as building energy-efficient renovation, using subsidies, incentives, and tax concessions, and to encourage financial institutions to increase credit support for technical renovation projects [69]. China's Ministry of Finance actively cooperates with the comprehensive work program for energy conservation and emission reduction and initiates various funding special programs, and the current financial support policies promulgated in China

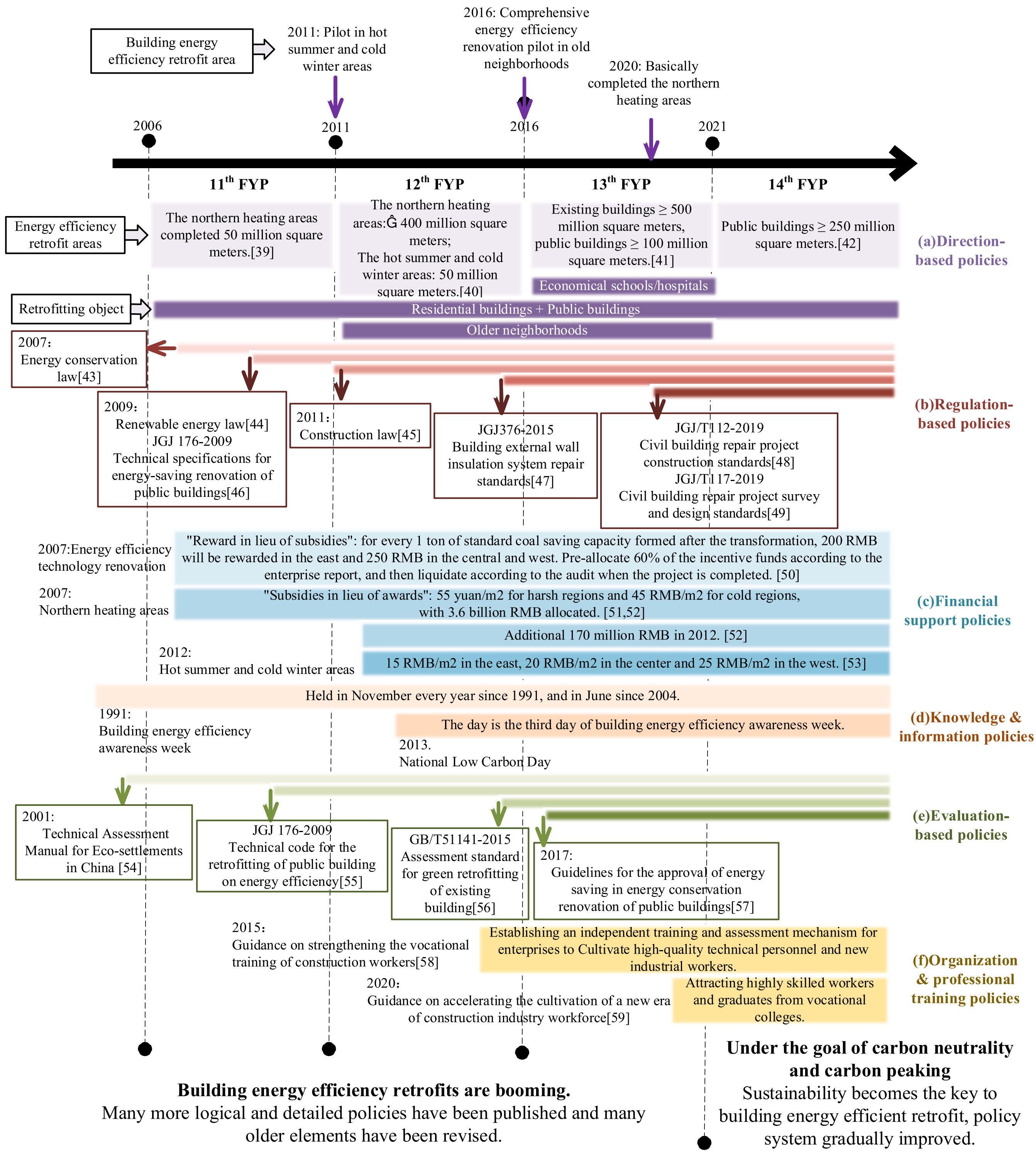

Fig. 5. Chronology of building energy-efficient renovation development and its milestones (the above-mentioned contents of this figure are extracted from the references of [43–63]).

regarding building energy-efficient renovation are summarized in Fig. 5 (c), including the corresponding economic incentives for energy efficiency measures such as the adoption of renewable energy [70,71], building energy efficient materials [72] and green lighting when implementing energy-efficient renovation in existing residential and public buildings. These documents all give detailed regulations on the areas of support, scope of usage, principles of incentives, application process, evaluation procedures, incentive methods, fund disbursement, and supervision and management of these incentive funds.

China has successively launched relevant documents, and the financial support through the "reward in lieu of subsidy" method (enterprises carry out energy-saving technology transformation and put into production for more than two years, and after achieving energy-saving effect and increasing tax revenue for the local area, they apply for energy-saving fund reward or subsidy to the higher authorities in the form of report according to certain procedures) is a commonly used financial measures. During the implementation of building energy-efficient renovation, the incentives fully mobilized enterprises and achieved multiple policy effects such as energy conservation, environmental protection, and improvement of people's livelihood, which were highly appreciated by the general public. Meanwhile, the governments are gradually realizing that the guidance of incentive policies can improve the vitality of the building energy efficiency industry, therefore increasing the intervention of retrofitting work in this way, expanding the financial investment, ensuring the performance of the used funding, and constantly revising and updating the incentive policies.

4.1.4. Knowledge & information policies

It is extremely important to increase the willingness of building energy renovation stakeholders to participate and to communicate to the public the achievements and advantages related to energy-efficient renovation. Knowledge & information policies about building energy efficiency in China are summarized in Fig. 5(d), mainly the National Energy Conservation Publicity Week held from 1991 to 2022 and the National Low Carbon Day from 2013 to the present. The theme of the 2022 Awareness Week is "Green and Low Carbon, Energy Saving First", and the theme is "Double Carbon". The former will explore the national strategy, technology direction and solutions for China's green energy-saving and low-carbon development under the background of "double carbon" [73,74], among which building energy-efficient renovation is one of the important contents. The awareness of energy efficiency in the whole society is increasing, and the promotion of comprehensive green transformation of the economy and society has become the highlight of the 2022 activities.

These activities show the remarkable results of building energy-efficient renovation work, energy-saving practices of key industry enterprises' buildings, energy-saving standards and energy-efficiency labeling publicity to the public through online energy-saving knowledge lectures and other forms. In addition to fully utilizing the advantages of traditional media such as TV, radio and newspapers, these activities also actively used microblogs, the internet, cell phones and other emerging media to increase publicity. For example, China Central Radio and Television (CRTV) launched a campaign on building energy efficiency under the title of "Green China Plus and Minus-Ministry of Housing and Construction Accelerates Green Transformation of Urban and Rural Construction" in its "Morning News" section. These promotional policies have a positive impact on raising residents' awareness of the necessity and importance of building energy-efficient renovation, thereby promoting a new phase of development for building energy-efficient renovation.

4.1.5. Evaluation-based policies

The whole life-cycle evaluation of energy efficiency and environmental performance of buildings is the essential to address sustainability issues. Some codes provide specific practices and operational requirements for government authorities in the field of building energy-efficient renovation, while evaluation standards are quantitative indicators for achieving building energy efficiency. In 2021, the Chinese government proposed to accelerate the update of energy efficiency standards, revised a number of mandatory national standards for energy consumption limits and engineering and construction standards, and increased awareness of energy efficiency and low carbon [46]. Fig. 5(e) presents the content and development history of China's building energy efficiency evaluation-based policies, including building energy efficiency evaluation standards and certification systems. Currently, China clearly stipulates that new buildings need to strictly implement mandatory energy efficiency standards and a market access system featuring energy efficiency labeling, while there are no clear regulations for buildings after energy-efficient renovation.

Since the evaluation of building energy efficiency is still in the initial stage, there are few corresponding specific evaluation standards, especially for the energy-efficient renovation of existing buildings. From the ''China Ecological Housing Technology Evaluation Manual'' to the ''Evaluation Standards for Green Renovation of Existing Buildings'', there has been a significant improvement in guiding the energy-saving renovation of ecological housing, from not emphasizing the light-weight relationship between different ecological strategies or technical measures to establishing an index system and adding weight calculations to clarify the evaluation indexes for each aspect of green renovation such as building space, structural materials, etc. [75], which will increase the current energy-saving renovation projects in the comprehensive selection of energy-saving measures. Only when all indicators reach 60 points or more can they pass the evaluation of eco-housing, thus regulating the green eco-housing construction market [76]. In addition, the evaluation priority has been changed from the results of project completion to the construction process of the project, divided into design evaluation and operation evaluation, and this project will be graded according to the evaluation results, and improvement measures will be proposed for the links that do not achieve the expected results [75]. However, there are still some shortcomings in the existing evaluation criteria for building energy renovation, such as the lack of correspondence between the amount of technology adopted and the score, and the lack of detail and number of cases, which need to be gradually improved after sufficient practice.

4.1.6. Organization & professional training policies

It is necessary to provide professional training for designers, contractors, construction managers, and workers for building energy-efficient renovation projects. This is because these professionals provide energy-efficient retrofitting services to homeowners in the evaluation and certification of building energy efficiency [77]. Currently, China has introduced several organizational and professional training measures related to the energy-efficient renovation, as shown in Fig. 5 (f). Professional training in building energy efficiency in China has broadly gone through three stages: from the initial suggestion that professionals need to receive relevant training, to the focus on establishing a relatively stable core pool of skilled workers, to the further recognition of upgrading the skills of construction workers through technological upgrades and completing the transition from traditional to new construction methods.

Successful completion of building professional training can improve the outcomes of building energy-efficient renovation projects, but currently training is still influenced by many factors, such as underestimating the effectiveness of training and poor levels of career guidance, which can lead to a generally low level of attention and poor implementation by construction companies. This is closely related to the fact that the existing professional training policy is focused on the level of opinions and guidance while lacking mandatory and supervisory management, and it is recommended that the relevant authorities continue to strengthen and improve the relevant policy contents. Meanwhile, it is recommended that companies draw more on successful training techniques for their activities. Some studies have shown that the utilization of participatory training methods such as photos and demonstrations can significantly improve effectiveness [78], thus addressing problems such as poor training quality.

4.2. Existing policy initiatives from the local government

The realization of building energy-efficient renovation goals at the national level needs to be tailored to local conditions, and supported and complemented by local policies. National policies, local policies and local authorities' governance capacity can simultaneously influence the successful implementation of building energy-efficient renovation. Based on the above-mentioned national policy analysis, it is essential to investigate targeted policies applicable to local development, formulated on the premise of national documents, from the representative provinces.

There are three main considerations in the determination of one representative province. The first is the climatic zoning, as different zones have their own meteorological characteristics such as temperature and precipitation, which imposes corresponding requirements on building design [79]. The second is the economic conditions, especially the annual gross domestic product (GDP) growth rate which becomes a decisive factor in measuring local sustainability, and to some extent also influences the building energy consumption requirements. The third is the social context, for instance, where development strategies conform to the regularities of economic development, which influence the planning and decision-making on key issues of building energy-efficient renovation within a certain regional scope over a longer period of time. Therefore, the promulgation of local policies should combine the climate, economic conditions and social background to enable better implementation of building energy-efficient renovation policies at the national level. Considering the above-mentioned factors, this paper selects the representative provinces of Zhejiang, Guangzhou, Shanxi, Heilongjiang and Yunnan (the specific characteristics of each province are shown in Table 2) to carry out the corresponding policy combing and analysis.

4.2.1. *Direction-based policies*

The discrepancies of the building energy-efficient renovation scale in the 14th FYP are largely attributable to the differences in the completion of the main indicators in the 13th FYP period, and the cumulative number of renovated building areas has been steadily increasing in various regions. For instance, the number of buildings retrofitted in Guangdong Province during the 13th FYP surpassed expectations, therefore the Guangdong Province has further increased the scale of building renovation in the 14th FYP based on available basic conditions and resources [81]. Among these five provinces, Guangdong has the largest area of existing buildings to be retrofitted [82], because Shenzhen, as the first pilot city for building energy-efficient renovation, has achieved significant results and can provide considerable experiences for the upcoming renovation projects. In terms of targets for retrofitting, Zhejiang Province [83], Shaanxi Province [84] and Yunnan Province [85] basically focus on energy-efficient renovation in old communities, which is related to the policy of implementing concurrent renovation of old communities and building energy efficiency during the 12th and 13th FYP. Zhejiang Province has the lowest number of planned renovation projects, as it also takes into account the building industry's emphasis on assembly-based intelligent new buildings. In summary, the formulation of local target policies, including the renovation area and contents of renovation, is closely related to the completion of its local targets in the previous stage, the pilot application and supporting efforts, the national-level policy direction, the economic development of the region, and other factors.

Table 2
Characteristics of each representative city.

Province	Climate Zones	Annual growth rate of provincial GDP [80]	Social background
Zhejiang Province	Hot summer and cold winter areas	5.2%	Yangtze River Economic Belt Development Strategy
Guangdong Province	Hot summer and warm winter areas	5.2%	Guangdong-Hong Kong-Macao Greater Bay Area Development Strategy
Shanxi Province	Cold areas	6.3%	Great Western Development Strategy
Heilongjiang Province	Severe cold areas	5.5%	Northeast Revival Strategy
Yunnan Province	Temperate areas	7.7%	Actively carry out the Yangtze River Delta industrial transfer to create a strong production base.

4.2.2. *Regulation-based policies*

Local legal policies are based on relevant national laws and regulations and combined with the actual conditions of each province, therefore there are significant differences in the emphasis of policies for each region. As an economically advanced province with a high population density, the legal regulations in Zhejiang Province make substantial additions from the national policy, mainly making explicit specifications on planning, retrofitting, technology application, incentives and legal liability, which emphasize measures such as building energy assessment and contractual energy management services [86]. The relevant legal policies in Guangdong Province where is characterized by a extensive volume of public buildings make selective deletions from the national policy, focusing on public buildings and highlighting the importance of incentive policies and approval specifications [87]. As one of China's former most significant coal-producing regions, Shanxi Province's policy emphasizes the development of energy-saving renovation plans for existing buildings after organizing surveys, statistics and analysis of energy-using systems, energy consumption indicators and life cycles of existing buildings [88]. Heilongjiang Province [89] and Yunnan Province [90] have improved the overall construction industry project quality supervision and market management system. Therefore, it is of paramount importance and necessity for local governments to have a comprehensive understanding of the region's building types, energy demands, unique energy structure, market management, and the effectiveness of existing policies. Based on this understanding, they can make appropriate adjustments to the policy focus of laws and regulations to promote the implementation of energy-efficient renovation works.

4.2.3. *Financial support policies*

All regions have established special funds to support the energy-efficient renovation of buildings, and the renovation costs are covered by the people's government at or above the county level in their own financial budgets. The support forms for these incentives are diversified, for example, Guangdong Province uses subsidies, awards and equity investment [91], Shanxi Province uses awards and subsidies [92], and Yunnan Province uses the combination of incentives and subsidies [93]. The allocation method also varies from different regions, such as Guangdong Province using a "pre-arrangement and post-liquidation" system combining the factor method and competitive evaluation, Zhejiang Province adopting a "classification measurement and separate aggregation" method that takes into account the economic development, self-assessment of performance and the factor weights in each region [94], and Heilongjiang Province assigning weights to local renovation funds based on the area of old communities, the number of renovated households, and performance evaluation factors [95]. Meanwhile, there are differences in the allocation of funds among various provinces, such as Zhejiang Province advancing 70% of the scale of special funds to lower departments in advance, but Guangdong Province refining the allocation to lower departments in advance according to the factor method. The main reasons for the variations in the forms of support, allocation methods, and funding distribution in fiscal policies across different regions include the following: 1) Variations in fiscal strength and resource allocation capabilities arise from disparities in the level of economic development. Regions with higher economic development tend to possess greater fiscal capacity and resources to allocate towards different sectors; 2) Different regions prioritize different sectors for development support. For instance, areas may emphasize funding for energy-efficient renovations in public buildings, support for key enterprises, or financial provisions for energy-intensive industries, and each sector may have its distinct funding supply mechanism.

4.2.4. *Knowledge & information policies*

Low-carbon publicity activities have been actively carried out in various places according to local characteristics with a diversity of activities [96,97]. Zhejiang Province continues to consolidate energy conservation and consumption reduction by popularizing knowledge of energy conservation and renewable energy, promoting energy-efficient products and publishing energy-saving posters, for example, Yueqing City responds to Zhejiang Province's request to carry out corresponding activities [98]. Various urban areas in Guangdong Province actively carry out activities to promote energy saving week in public institutions, for example, Huizhou City invited experts from energy saving service companies to use exhibition boards for explanations [99]. Shanxi Province organized online green, low-carbon, energy and water conservation knowledge prize competitions, sent public service promotional messages and offline energy shortage experience activities [100]. Heilongjiang Province promoted the creation of conservation-oriented organs, conservation-oriented hospitals and campuses during the publicity week [101]. Yunnan Province produced and broadcast energy-saving and low-carbon publicity videos in some public institutions and bus stations [102]. The different geographical environments, urban–rural development conditions, and energy production and consumption levels in each province determine the varying degrees of energy pressure and environmental challenges they face. As a result, there are evident differences in public awareness, participation, and acceptance of building energy efficiency renovations. It is crucial for local governments to choose appropriate low-carbon promotion methods based on their development needs.

4.2.5. Evaluation-based policies

The implementation of building energy-efficient renovation projects in all regions needs to meet the current standards in line with other relevant national and provincial standards, and each organization is encouraged to summarize its experience and respond to suggestions in time during the implementation process. As the relevant parameters (e.g., heat transfer coefficient, shading coefficient, thermal performance of external windows) are determined on the basis of meteorological data (e.g., annual sunshine hours and radiation intensity) and building climate zoning characteristics, the contents of the standards vary considerably from different regions, even providing specified climate parameters for different urban areas and counties. Building energy-efficient renovation requires reference to building energy design standards, and ventilation and air conditioning systems are considered in all five provinces. Heilongjiang [103], Shaanxi [104] and Yunnan [105] Provinces provide a design basis for envelope structures, while Guangdong [106] and Zhejiang [107] Provinces require sun-shading design. During the process of developing local energy-efficient renovation standards, there is a tendency to prefer the use of efficient and suitable air conditioning equipment and humidity regulation methods. There is also a focus on the waterproofing, moisture control, insulation, and thermal insulation capabilities of the building envelope. Each region makes flexible adjustments based on its specific climate characteristics to improve energy utilization efficiency and indoor comfort.

4.2.6. Organization & professional training policies

Various regions have actively adapted vocational training for construction workers, with commonalities including the adoption of a real-name system for construction workers, unified standards and information management, and a combination of video broadcasting and practical exercises for the literacy level and characteristics of construction workers, but each province will make policy innovations according to local characteristics. Zhejiang Province has established a database of examination questions for the corresponding trades and recommended the usage of professional training materials that meet occupational standards [108]. Guangdong Province implements graded and classified training, divided into technician and senior technician training and assessment, intermediate and senior technician training and assessment, and general worker and junior technician training and assessment [109]. Shaanxi Province has established the mechanism of linking construction workers' wage levels to their vocational training levels, so as to motivate construction workers to participate in vocational training and obtain grade certificates [110]. Heilongjiang Province fully utilizes the "Heilongjiang Construction Vocational Training and Employment Service Platform" to incorporate relevant policies, techniques and standards into the continuing education of registered practitioners [111]. Yunnan Province attaches importance to training and assessment for qualification approval of construction engineering enterprises, and teaches key points of qualification evaluation of construction, supervision and testing enterprises [112]. It is recommended to facilitate experience sharing and collaborative learning among different provinces, aiming to exchange best practices and training models in building energy efficiency renovations. This collaborative approach would enable the exploration of innovative pathways for training construction workers. For instance, it could involve the exchange of renowned experts for training and guidance, the establishment of joint training centers or collaborative institutions, and the collaborative development of training courses.

4.3. Summarizations and discussions of current policy initiatives

A systematic analysis of the relationship between the above six types of policies (shown in Fig. 6(a)) reveals that the policies are not completely independent but support and interact with each other. Direction-based policies can provide important guidelines and roadmaps for other energy efficiency policies [113]. In turn, the feedback from other policies will similarly change their contents for the next stage. Financial support policies serve as an economic guarantee for organizing professional skills training, raising public awareness, implementing legal standards and enforcing building energy efficiency assessments [114]. Evaluation-based policies can assist in determining the retrofitting potential of existing buildings [33], and the results of the assessments serve as a basis for financial investment. The willingness of residents to participate in retrofitting can be increased by disseminating knowledge of policies related to energy efficiency retrofitting of buildings to the public, thereby supporting the implementation of other policies [115]. Organization & professional training policies can effectively contribute to the improvement of skill levels [33,113], and therefore being used to facilitate the implementation of evaluation-based policies. Inevitably, there are various barriers to the implementation of policies in terms of financial, evaluation, training and knowledge, which can be overcome by the establishment of targeted legal documents [116], and it is also necessary to set the minimum requirements for energy-efficient renovation of existing buildings.

National and local building renovation policies are constantly being updated, streamlined, and supplemented based on the experience of past implementation, enabling actively exploring new approaches to modern building renovation. The relationship between national and local policies (as shown in Fig. 6(b)) has been sorted out, with the central government assigning specific requirements and tasks for building renovation to local governments, and local governments formulating their "14th FYP" based on the completion of local "13th FYP" tasks and summarizing shortcomings in a timely manner. National legal and evaluation-type policies are applicable to each climate zone, while local policies are supplemented and refined with specific provisions based on local characteristics. Local policies such as economic incentives, professional training, and public awareness are inherited from national policies and require active implementation of relevant measures, such as the establishment of dedicated funds, unified assessment standards, and energy efficiency promotional weeks to support building energy renovation activities. Conversely, some local successful experiences will be absorbed by the central government, for example, in 2017, the Ministry of Housing and Urban-Rural Development (MOHURD) agreed to the 23 local standard provisions proposed by Heilongjiang Province for the record of "local standards for engineering construction in China" [117].

These renovation plans are largely dependent on the scale and productivity of building industries, and incentives for energy-efficient renovation are inextricably linked to local economic conditions.

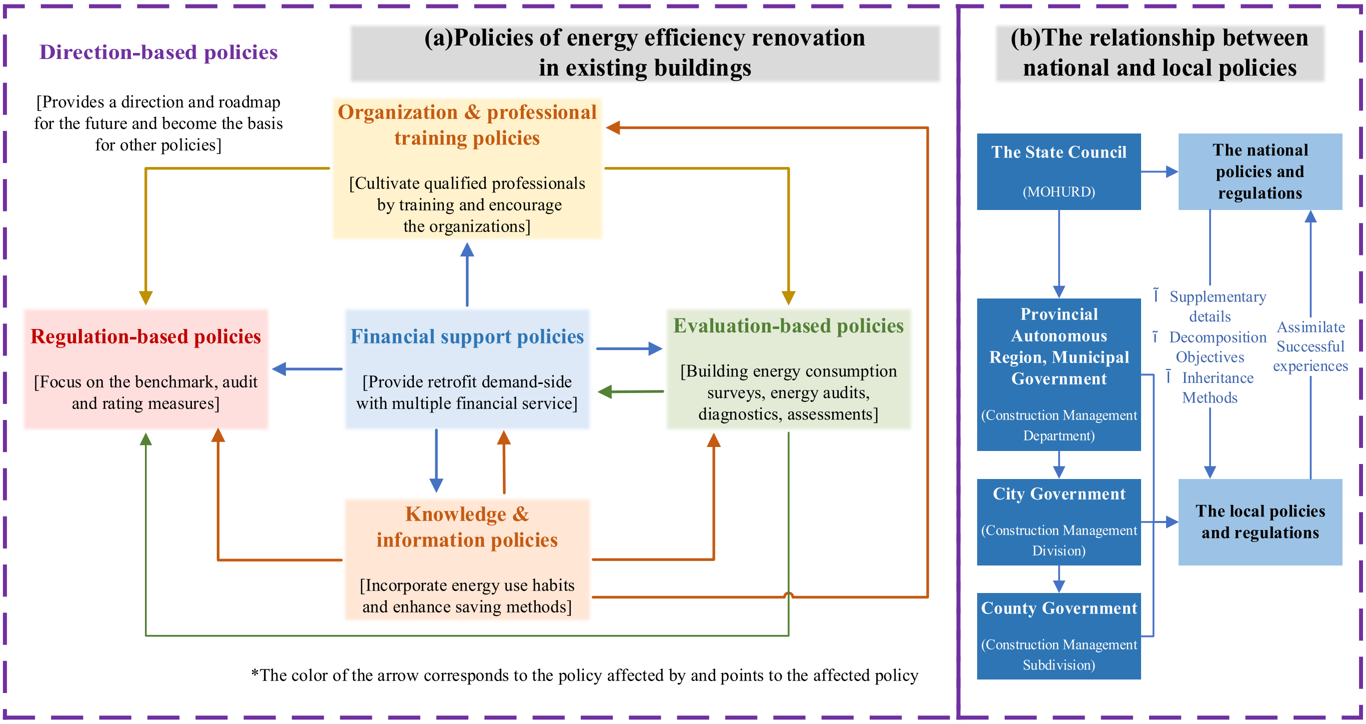

Fig. 6. Relationships between the different types of building energy-efficient renovation policies.

Climate zoning directly influences the formulation of design standards policies, and professional training, and public awareness are related to the organizational structure of the government, so the manifestation of various policies varies between provinces. The related policies and management systems of Guangdong Province and Heilongjiang Province are more comprehensive and sophisticated. The main reason is that in these two provinces, Shenzhen and Harbin Cities have been listed as pilot projects for building energy-efficient renovation in China, which have positively influenced building productivity through the most appropriate approach and policy tools, technological innovation, industrial restructuring and resource allocation [118], and a large number of priority projects with complete technical information and feasibility studies have been completed and have accumulated valuable practical experience. The coastal province [97] of Zhejiang attaches great importance to the development of the building industry and invests large amounts of government funds for the promotion of new technologies and the training of building talents, and policies related to building energy efficiency are relatively well-established but mainly for new green buildings. In contrast, Shanxi and Yunnan Provinces have slightly less policy innovation and support, with provincial governments playing the role of transmitting policy and information. However, with high provincial GDP growth rates and large inventories of existing buildings, both places have great potential for building energy-efficient renovation, and it is recommended that local governments pay more attention and accelerate the expansion of local policies.

5. Policy polit initiatives of building energy-efficient renovation

Actually, improving the energy efficiency of existing buildings is more challenging than that of new buildings because most policies to increase building energy efficiency are mainly targeted at new buildings, together with insufficient financial support for building energy-efficient renovation, immature sill levels, and inadequate development of related industrial supports [119]. To maximum the energy efficiency potential of existing buildings, in 2011, the Chinese government officially launched a demonstration of energy efficiency retrofits based on the 'Notification of Future Promoting Energy Efficiency of Public Buildings'. This notification identified four cities with relatively developed economies and mature market systems (i.e., human resources, financial instruments, and building technologies)-Shanghai, Tianjin, Shenzhen, and Chongqing-to carry out building energy retrofit pilot projects. This notification required that no less than 4 million square meters of public building area should be completed and that energy consumption per unit area should be reduced by more than 20% [120]. Among them, Tianjin is located in a cold region of China and necessitates the centralized heating model in winter, while the other cities are in the south where the usage of clean energy is more widespread compared to the north.

To further accelerate the process of building energy-efficient renovation, the Chinese government launched the second batch of pilot cities for energy-efficient renovation of public buildings in 2015. The second batch of pilot cities included cold climate Shandong Province (i.e., Qingdao and Jinan Cities) and Qinghai Province (i.e., Xining City), cold climate Heilongjiang Province (i.e., Harbin City), and hot summer and warm winter Guangxi Province (i.e., Baise City) and Fujian Province (i.e., Fuzhou and Xiamen Cities). This document also proposed higher requirements for energy-efficient renovation area, where Chongqing was twice selected as a pilot city due to its remarkable building energy-efficient renovation. As can be seen in Section 4, the development of local policies is inextricably linked to economic development, climate characteristics, and other influencing factors. Fig. 7 provides a clear depiction of the locations and climatic zones of two batches of energy-efficient building renovation pilot projects in China. These pilot projects are differentiated by two distinct colors. Additionally, it presents a list of notable local policies implemented in benchmark cities that effectively guide energy-efficient renovation efforts within their respective regions. This information is crucial in facilitating the progress of energy-efficient renovation initiatives. Table 3 lists the progress of the two batches of pilot cities' energy-efficient renovation targets as of 2020. It includes the target area, completed area, number of projects, and average energy-saving rate. This table offers a visual representation of the project implementation and energy-efficient renovation levels across the pilot cities. It also demonstrates the effectiveness of the targeted policies highlighted in Fig. 7. Furthermore, this section provides a

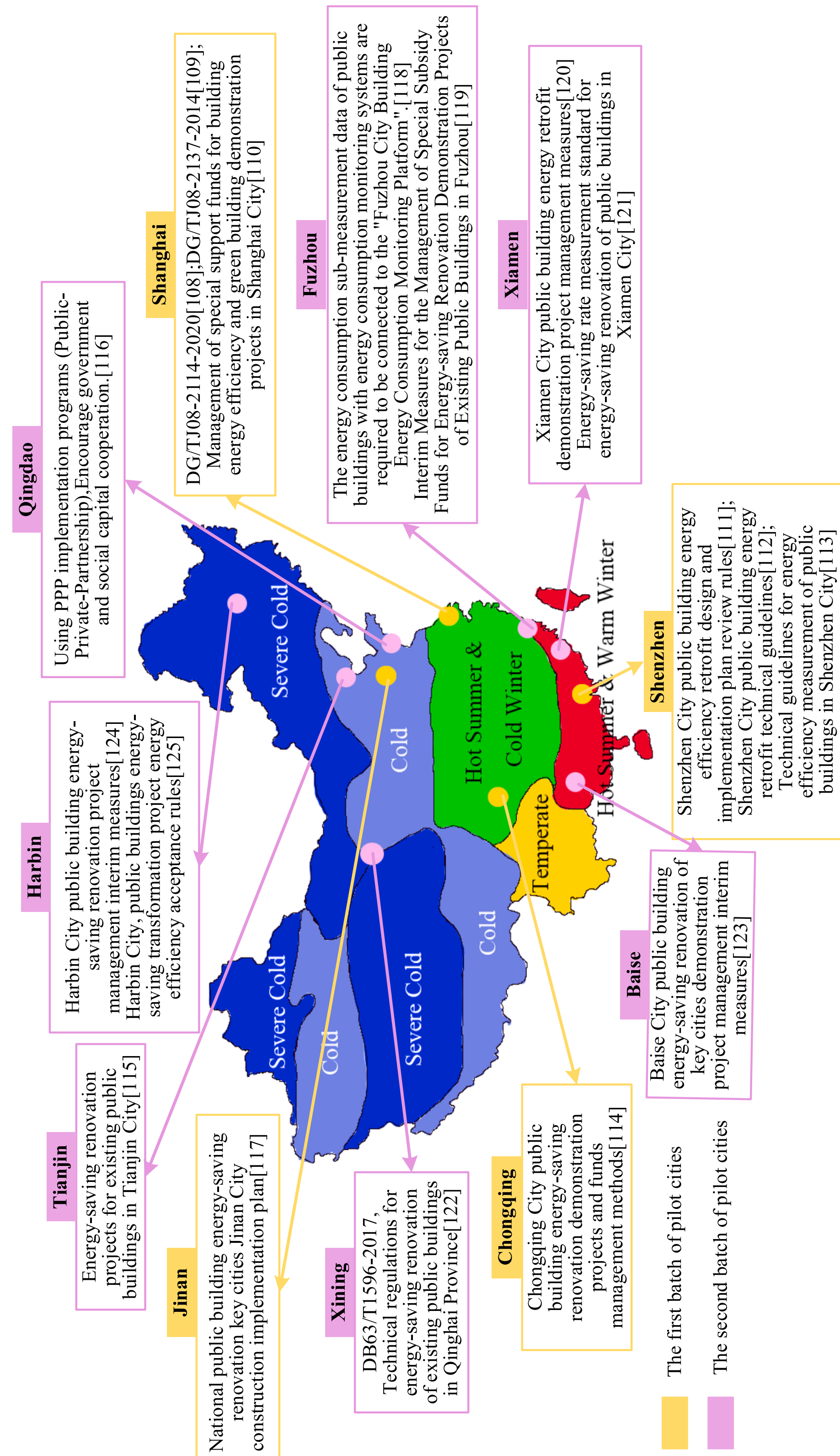

Fig. 7. The representative policy initiatives for two batches of pilot cities and their geographical climate regions [121–138].

comprehensive analysis of the reasons behind the inadequate efficiency of some typical cities in advancing their building energy-efficient renovation projects. Such insights serve as valuable experiences for future projects in similar cities in the next phase.

(Note: the data on the renovation area and number of projects in the 11 pilot cities were obtained from the study of Chi [139].).

As pilot cities for building energy retrofits have received widespread attention with powerful policy support, the series of implementation efforts have a significant positive impact on improving the overall energy efficiency of buildings. The Chinese government intends to explore

Table 3
The completion status of task objectives for the two batches of energy-efficient renovation pilot cities.

Batch	City	Task area ($\times 10^4 m^2$)	Completed area ($\times 10^4 m^2$)	Number of projects	Average energy-saving rate
1	Shanghai	400	400	73	20%
	Shenzhen	400	407	167	20%
	Chongqing	400	408	99	22.50%
	Tianjin	400	405	102	20.30%
2	Qingdao	320	357	34	21.60%
	Jinan	230.4	234.5	27	23.40%
	Fuzhou	210	223.9	50	22.50%
	Xiamen	300	303.9	47	23.20%
	Xining	265	265	35	20.70%
	Chongqing	350	354.3	82	21.80%
	Baise	243.5	243.7	102	15%
	Haerbing	200	204.7	77	23.90%

policy innovations tailored to local characteristics through these pilots [140], so as to provide reference and guidance for the implementation of building energy retrofit projects in other cities with similar resource environments and economic development patterns as these pilot cities. Fig. 7 also shows the important policies launched and results achieved by the two batches of key cities for building energy-efficient renovation, including incentive policies and energy efficiency measurement standards. In the special inspection of the work progression of building energy efficiency in 2016, the first batch of key demonstration cities have all completed their retrofitting assignments according to the set targets and successfully passed the inspections by the Chinese government (Ministry of Housing and Urban-Rural Development). Among the second batch of key cities, Chongqing (additional tasks), Jinan, Qingdao, and Xining Cities had completed more than 35% of their retrofitting tasks, while Xiamen (adopted in 2019 [141]), Harbin, Fuzhou, and Baise Cities had made relatively slow progress in their retrofitting works [142].

A summary of successful experience of the above-mentioned demonstration cities for building energy-efficient renovation shows that the demonstration cities have initially built a policy management system, basically preparing policy documents such as organization and implementation plans and financial management methods. The pilot cities have initially established a technical standard system for building energy-efficient renovation. Each pilot city has initially established a technical standard system for building energy-efficient renovation, with cities such as Shanghai and Xiamen upgrading it to a local standard. The above-mentioned cities have introduced some incentive policies, mainly including three forms of financial subsidies, tax concessions and energy-saving funds, and improved financial products such as green credit, green funds and green bonds, thus broadening the investment and financing channels for building energy-saving services. Some demonstration cities have initially established market management model (owners are not required to invest capital, and social capital such as energy service enterprises invest in energy-efficient renovation initially, and can apply for financial incentives after the renovation being completed and achieving the standards.), which can provide public building owners with energy-saving consulting, diagnosis and other whole-process services. These main cities for energy efficiency improvement in public buildings have initially formed a model of energy-saving renovation of public buildings with market mechanisms as the primary focus and government guidance as the supplement.

6. Implementation barriers for policy initiatives of building energy-efficient renovation

Many existing studies have been carried out on the barriers related to the advancements of energy-efficient renovation for existing buildings. For instance, Putnam et al. [143] found household participation, development of local supply chains, and government financial and regulatory support programs as the main barriers in their analysis of building energy-efficient renovation in the UK. Alam et al. [114] summarized the building energy-efficient renovation challenges faced in Australia to include four components: building efficiency assessment, financial funding, government procurement models, and public awareness. Caputo et al. [144] analyzed the barriers to energy-efficient renovation of public buildings in Italy, where factors such as government policies and the behavior of major stakeholders (occupants and investors) were considerably influential. Du et al. [145] adopted questionnaires, interviews, and factor analysis to investigate the barriers to building energy-efficient renovation in China from five perspectives: stakeholders, policies and regulations, auxiliary resources, profitability, and technological adaptability.

Due to the unique characteristics of the government's role and authority, policy development procedures, economic development model, and the current development status of the building industry, China has its own distinct limitations, barriers, and challenges in promoting the process of building energy-efficient renovation. Furthermore, because of the different building energy consumption characteristics, energy efficiency retrofitting requirements, and multiple stakeholder involvement, building energy-efficient renovation in China has formed a complicated system. Based on the existing studies and Chinese national circumstances, this section classifies the barriers to building energy-efficient renovation into four categories from the perspective of the target audience: governments, householders, enterprises, and researchers. The relationship between these four audiences and related barriers are systematically sorted in Fig. 8, and their corresponding implementation barriers are categorized in Table 4.

In addition to the internal barriers among stakeholders presented in Table 2, there are several challenges in communication and collaboration among different entities that can impact the smooth progress of energy efficiency renovations. These challenges include: 1) Stakeholders, such as the government, businesses, and users, have different priorities and interests. While the government may prioritize the promotion of energy efficiency policies, businesses may focus on economic benefits, and users may prioritize comfort and cost-effectiveness. This divergence can lead to a lack of consensus and hinder decision-making processes [154]. 2) Stakeholders face constraints in terms of funding and resources. The government needs to allocate funds to support energy efficiency renovation projects, businesses seek corresponding financial support, and research institutions require research funding and equipment support. Insufficient availability of funds and resources can result in project delays, resource wastage, and suboptimal outcomes. 3) Government policies and standards for energy efficiency may not fully align with the actual needs and technological capabilities of businesses and research institutions. This misalignment can create barriers to collaboration between these entities. 4) There is often an imbalance in terms of professional knowledge and information among stakeholders. The government, research institutions, and businesses may possess more expertise and information, while users may be at a disadvantage. This information asymmetry can lead to communication difficulties, inaccurate decision-making, and resource wastage [155]. Therefore, it is crucial to clarify the responsibilities of the four major stakeholders and identify their intersecting interests. Establishing scientific incentive mechanisms, efficient policy implementation pathways, and information-sharing platforms are key to addressing the challenges among stakeholders. These specific strategies will be further elaborated in the following sections.

7. Future prospective and recommendations for promoting policy initiatives of building energy-efficient renovation

Based on the analysis of implementation barriers to building energy retrofit policies in Section 6, this section combines existing studies to make rationalized recommendations for the upgrading of building energy retrofits in China. It requires the aggressive invocation of relevant

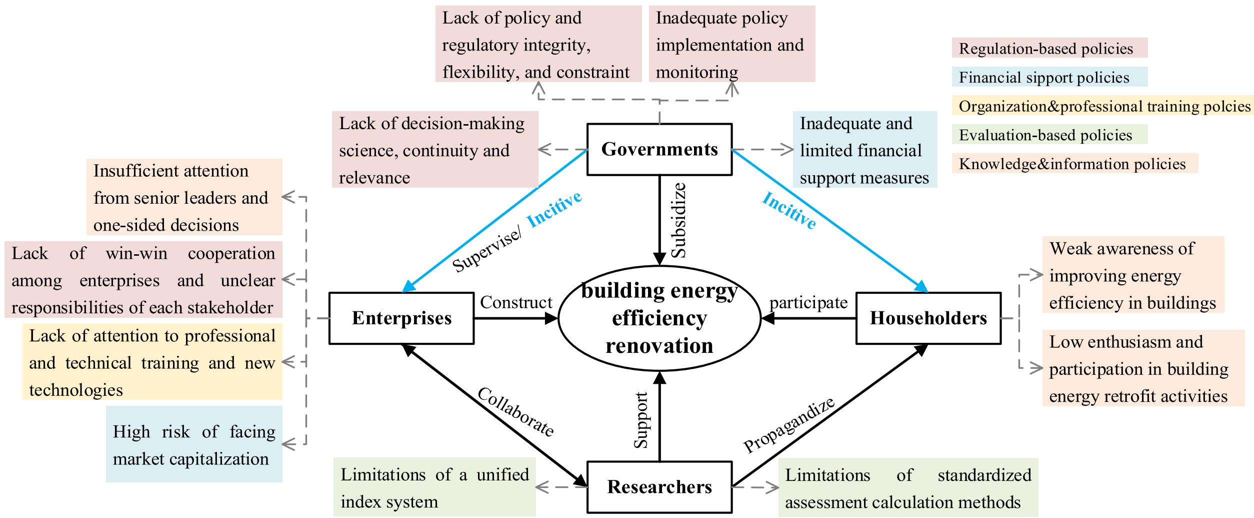

Fig. 8. Barriers and relevance framework of the implementation process of policies related to building energy-efficient renovation.

legal, economic, evaluation, information, training, and other policy tools in order to effectively promote building energy retrofits to achieve good results in practice across China. Fig. 9 presents an implementation roadmap to effectively promote energy-efficient renovation in buildings. Next, the deepening analysis will be gradually addressed to the main contents and operational considerations of each section.

7.1. Establishing comprehensive energy retrofitting regulations

Building energy-efficient renovation regulations will effectively promote the implementation of retrofit activities. The existing regulatory framework for building energy efficiency, as shown in Fig. 10, is mainly composed of three parts: the legal system for building energy efficiency, the building quality supervision system, and the building energy efficiency inspection system. However, the current regulatory framework mainly focuses on new buildings, and the parts involving energy-efficient renovation of existing buildings are relatively few and not well developed, moreover, there are generally few mandatory requirements for the application of energy-efficient technologies or measures in building retrofitting [156]. In addition, the implementation of the existing regulations suffers from inadequate inspection of energy efficiency in existing buildings and falsification of indicators, resulting in a large number of poorly retrofitted buildings being labeled as "green" [157].

Therefore, it is necessary and urgent for China to establish more comprehensive building energy retrofit regulations and strengthen related retrofit regulatory measures. Firstly, reasonable and enforceable legal provisions need to be supplemented and developed, especially for the specific process of building energy retrofitting. Then, it is essential to strengthen the collection, integration, and extrapolation of basic energy consumption statistics [159], which can then be used as a baseline for policy formulation to ensure the rationalization and long-term effectiveness of fundamental policy decisions. In addition, it is necessary to learn from the advanced practices of Austria, Finland, France, and other countries, and local governments should make corresponding adjustments according to the characteristics of their own development, with the approval of the central government [32], so as to enhance the consistency and timeliness of these promulgated policies.

On the other hand, effective management measures to improve the building monitoring and inspection system will become a critical factor to improve the effectiveness of regulation enforcement, especially to strengthen the inspection and punishment of the retrofitted buildings' energy performance. Therefore, the government's regulatory authority in the field of building energy-efficient renovation needs to be explicitly authorized by legislation to decrease the phenomenon of exceeding authority and irresponsible disorder. Meanwhile, a bottom-up strategy can effectively overcome the limitations of a single top-down policy model [160], and thus effectively address the inefficiency of implementing energy efficiency retrofit measures. Moreover, it is necessary to integrate temporal and spatial information in order to achieve cross-departmental and cross-system business cooperation in the implementation of building energy-efficient renovation measures [161].

7.2. Increasing public awareness of energy-efficient renovations

The implementation of any measures requires the active public participation to be the final destination. However, the awareness and willingness of households to participate in building energy renovation measures are generally very low, which is largely due to the limited availability of relevant information, insufficient publicity, and complex implementation procedures and insufficient support for economic policies. Therefore, it is essential to increase public awareness and acceptance of building energy-efficient renovation in order to achieve the government-set building energy efficiency targets.

In terms of increasing public accessibility to information on building energy renovation, Baumhof et al. [162] proposed that the optimal building energy retrofit houses and their owners' sharing could serve as reliable key connections to disseminate relevant know-how and information to friends, family, and communities. Hrovatin et al. [163] suggested designing reasonable public energy professional advisory networks (media and internet) to expand the influence of building energy retrofit policies. Regarding the improvement of incentives for occupants, Dolšak et al. [164] point out that household financial status was a determining factor for householders to accept energy efficiency retrofitting activities and proposed to integrate it into the threshold for applying for special funds. Meanwhile, they also advocated the implementation of a transparent and simple subsidy application process to decrease the barriers encountered by households during the application process.

Overall, it is essential to raise public awareness of energy-efficient renovation from social activities and media networks, and to protect residents' rights through certain financial measures to increase their enthusiasm for renovation activities. The government organizes a series of social activities, such as inviting volunteers to participate in energy advisory networks to provide gratuitous experience sharing and disseminate knowledge to friends, relatives, and even broader groups [163]. The government actively disseminates the latest achievements and technological innovations in building energy-efficient renovation

Table 4
Classification summary of implementation barriers to building energy-efficient renovation.

Category	Descriptions of the corresponding barriers in the subcategories
Governments	**Lack of decision-making science, continuity and relevance** i) Building energy consumption data was managed by different government departments and institutional coordination systems were not in place, so it is difficult to obtain all the basic data for building energy efficiency assessment [33,146]. ii) The government did not fully consider operational emission reduction, policy feasibility and other factors in the decision-making process and relied excessively on research data from papers, without prioritizing the quality of renovation [147]. iii) Relevant policies were developed relatively short-term (e.g., FYPs), and their long-term continuity was hampered [147]. iv) Some local governments did not formulate policies that are more conducive to local development based on local realities, but choose to copy or apply the central government's documents, making it difficult to maintain the timeliness of policies [146,148,149]. **Lack of policy and regulatory integrity, flexibility, and constraint** i) China lacked the specific legislative authority for building energy retrofits, the use of terms such as feasibility was vague or inconsistent, and outdated policy documents were not updated in a timely manner [33,119,149,150]. ii) Mandatory mandates and complex frameworks for energy efficiency retrofits can affect retrofit quality and implementation efficiency [33]. iii) Although legal penalties exist for failure to meet targets corresponding to building energy retrofits, they were difficult to enforce in practice due to a weak legal system [33,149]. **Inadequate policy implementation and monitoring** i) The promotion of energy-saving building renovation was not received sufficient attention from local governments, and there was a serious shortage of personnel at all levels of housing and urban–rural construction departments set up to specifically manage this part [148]. ii) Misaligned management of multi-departmental linkage work leaded to asymmetric policy information and inefficient implementation [148]. iii) Ineffective monitoring of energy consumption in retrofitted buildings made it difficult to guarantee the quality of energy efficiency [150]. **Inadequate and limited financial support measures** i) Current incentives were top-down, open-loop structures without the necessary interaction processes and were fragmented and misaligned [33,119]. ii) Some of the special funds support content was seriously missing, such as new building energy efficiency technologies, product investment and development [149]. iii) Insufficient access to information on financial support (e.g., subsidies, low-interest loans, tax breaks, special funds and incentives) and the difficulty of obtaining building energy consumption data in most cities could make the application process for certification complex and time-consuming [33].
Householders	**Weak awareness of improving energy efficiency in buildings** i) Few networks and media considered to building and promote the establishment of building energy efficiency retrofitting platforms, with the lack of activities including community organizing and experience sharing, lack of training courses for end users and follow-up uninterrupted feedback [19]. ii) Insufficient software development to collect electricity consumption data from customers resulted in not helping customers understand their own energy consumption footprint, so most customers were unaware of the actual consumption and savings potential of their home buildings [33,119]. iii) As a result, the public generally believed that government plays a key role in energy efficiency retrofits, while ignoring its own connection to improving building energy efficiency. **Low enthusiasm and participation in building energy retrofit activities** i) Users were unsure of the profitability of building retrofits due to high initial investment and long payback periods [33,119]. ii) Residents expressed anxiety about the disruption of normal building use and the potential for confusion, stress, and error caused by remodeling activities [118]. iii) There were significant disagreements among tenants on contract duration, energy efficiency verification, and generally long negotiation cycles [19,118]. iv) There was a mismatch between the energy performance of the building and the demands of the consumers (e.g., school district housing, housing comfort), and many consumers even said they did not need energy-efficient technology [19,151]. v) When the amount of resources invested in retrofitting exceeds a threshold that can cause the market to deviate from expectations, consumers may have to bear the corresponding risk [19].
Enterprises	**Insufficient attention from senior leaders and one-sided decisions** i) Corporate executives believed that the investment in reducing building energy consumption may generate less profit than the equivalent resources invested in other performance, so correspondingly the resources allocated to energy-efficient technologies were limited and even oppose the use of any non-mandatory energy-efficient technologies [145]. ii) Most businesses had limited and asymmetrical access to building energy efficiency information, and considered decisions and barriers that were not based on audits or advice from energy management professionals [152]. As a result, few businesses were involved in the practice of building energy efficiency retrofits due to a weighing of costs and benefits. **Lack of win–win cooperation among enterprises** i) Companies and organizations that are able to conduct research and input into energy efficiency technologies were often reluctant to make their results or information available to the public, and small businesses had more resource constraints that make it difficult to do this part of the development on their own [145]. ii) Linear sequential building retrofit process leaded to shifting of responsibilities between firms at each stage of design, construction and operation [119,145,148,149]. **Lack of attention to professional and technical training and new technologies** i) Lack of professional education and training in building energy retrofitting leaded to low quality of related professional design, management and construction technicians [19,33,119,151]. ii) Many retrofit projects were limited to adopting past experiences, simply replacing existing equipment without involving new technologies, or some immature energy-saving technologies were difficult to adopt or even produce side effects due to improper design and misuse [19,33,119,151]. As a result, the lack of talents, equipment, and technology caused the ineffectiveness of the projects, and made it more difficult to guarantee the quality of building energy efficiency retrofits. **High risk of facing market capitalization** i) An energy efficiency management system adapted to the requirements of the market economy had not yet been established, and most public buildings used the traditional market business model, with incentives basically relying on government financial expenditures (including national bonds and international cooperation programs) [118]. ii) Limited funds to support multi-channel financing (e.g., market financing) and high loan thresholds from financial institutions, mainly because the environmental and social benefits achieved from building energy efficiency retrofits cannot be a specific financing condition [33,118,119,148].
Researchers	**Limitations of a unified index system** i) There was no unified system of widely applicable indicators for energy efficiency retrofits in Chinese buildings due to factors such as building type, construction time, and geographic location, which makes energy efficiency assessments by different third-party auditors not comparable from project to project or from site to site [33,118,149]. ii) Existing energy efficiency evaluation techniques and tools were inadequate, for example, energy metering systems were only available for a few buildings with district heating that had installed heat metering or specified equipment, which leads to low reliability of the data obtained from inspections and increases the workload of local governments [118,149]. **Limitations of standardized assessment calculation methods** i) The existing literature lacked strong empirical evidence and support, and the methods used were too simplistic to reflect the complexity of real life conditions, for example, the analysis of the

(*continued on next page*)

Table 4 (*continued*)

Category	Descriptions of the corresponding barriers in the subcategories
	impact on occupant behavior was often neglected in existing building energy performance analysis [153]. ii) Most researchers had focused too much on minimizing short-term costs without fully considering the effect on the long-term economic performance of building projects, and establishing calculation methods for assessing energy consumption of building energy retrofits from the perspective of building sustainability and informatization [153].

through social media that cater to various demographic groups, including professional articles, broadcasts, and documentaries, for instance, the environmental documentary "Under the Dome" released in China had remarkable success [165]. In addition, the government should optimize the economic support framework by considering the income of the residents and simplify the various financial incentives (e.g., tax breaks, subsidies, preferential loans, and incentives) offered by the national government [166], preferably by providing accompanying professional consulting services to the applicants as well as by providing a comprehensive campaign for this purpose.

7.3. Upgrading energy efficiency retrofitting standards for existing buildings

Building energy efficiency standards are considered one of the most effective measures to decrease building energy consumption, however, there is still a lack of the widely implemented energy efficiency assessment index system for building energy retrofits in China. Chinese building energy efficiency standards consider the craftsmanship and heat transfer coefficient of the envelope as the main judging criteria for measuring energy efficiency, while the energy consumption limits for heating and air conditioning are used as secondary indicators, and thus it is difficult to measure the specific energy consumption of buildings in practical application.

The existing building energy efficiency standards in various countries mainly divide into two categories. Firstly, the countries represented by the United States, Canada, and Japan use various technical parameters as indicators to guide energy-efficient building design and other aspects, transforming energy conservation and emission reduction into new economic growth points, and China also favors this category [167]. The second is that the energy consumption of systems and components as indicators to constrain the energy consumption of building operation, and to achieve a direct correlation with carbon emissions to ensure overall building energy efficiency, and the EU countries are the most typical in these aspects [168].

Considering the advantages of building energy efficiency standards in Europe and the US, it is suggested that Chinese building energy-efficient renovation efforts require more attention to actual energy consumption to control overall energy consumption, which requires that the energy efficiency standard system gradually change from a single performance indicator stage to the stage where overall energy consumption is the binding indicator. For instance, Guo et al. [169] built a three-level evaluation index system for public building energy efficiency based on the "input-output" of the construction industry, covering seven major service aspects such as cooling and heating systems, and correlating the energy consumption of buildings with their service quality to fully reflect the actual energy performance of existing buildings. However, the current energy situation and special national conditions dictate that China's building energy efficiency standards cannot blindly copy the established building comfort and service quality standards of developed countries.

7.4. Promoting the applications of building performance simulation in building retrofitting planning

Considering the fact that the building industry has not yet established a standardized and long-term method for evaluating building energy efficiency that closely matches the practical situation, the application of building performance simulation in building energy retrofit planning has demonstrated obvious advantages. Compared to the traditional "trial-and-error" approach, building performance simulation can break through the limitations of time-and-space to obtain the optimal design by setting multiple working conditions and comparative analysis, thereby significantly improving retrofit efficiency, decision-making efficiency, and decreasing unnecessary waste of resources [170].

In recent years, Li [171] proposed a genetic algorithm-based neural network that combined parametric building information modeling to automatically generate simulation results and energy consumption predictions to provide effective performance data for building retrofit design. Ceballos et al. [172] developed a simulation model in JAVA programming language to evaluate the energy consumed by existing commercial buildings and the potential impact of different energy efficiency retrofit measures. These initiatives indicate that the academics have devoted sufficient attention to performance simulation related to building energy retrofitting, however, the acceptance and usage of these assessment methods by companies remains relatively limited due to the less sophisticated and lack of cost-effective simulation platforms.

Therefore, the government should launch relevant incentive policies to actively encourage enterprises to use building performance simulation tools in the pre-retrofit stage of building energy efficiency to increase the scientificity of decision-making on energy efficiency retrofit measures [173]. Meanwhile, the government should encourage academics to focus their research on combining various types of algorithms to build more accurate building energy prediction models and try to overcome the limitations of the assessment methods mentioned in Section 6. In addition, the government should encourage strengthening the cooperation between enterprises and research institutions to achieve model optimization oriented by realistic requirements and to promote advanced building simulation theory research results to practical applications.

7.5. Encouraging the requisite capital investments

Financial support for building energy retrofits mainly comes from government incentives, and existing business models and financing methods are difficult to adapt to market demands. Nevertheless, green capital investment can promote increased research and development investment and green technology innovation [174], which is an effective solution to alleviate the above dilemma. However, the current situation of high energy consumption and pollution in China's construction industry has a significant deterrent effect on green investment benefits [175], as well as government-imposed environmental policies may increase the uncertainty of investments [176]. Therefore, green investment benefits are currently relatively low in China, which has resulted in less capital flowing into building energy efficiency retrofitting. Considering this aspect, Devine et al. [177] suggested that the developing countries should attract direct investment from developed countries, which facilitates the building projects to enter the local market, where the building energy efficiency certification activities can effectively reflect the results of the examination of new technologies. Debrah et al. [178] proposed that financial institutions, including banks and funds, are the largest contributors to green investment, and also encourage green development funds, green insurance, and other green financial products. Razmjoo et al. [179] presented that the development of emerging financial technologies (e.g., big data, and blockchain) could decrease the risk of green financial investments.

In summary, establishing the market-oriented financial system and encouraging social capital to participate in building energy-efficient

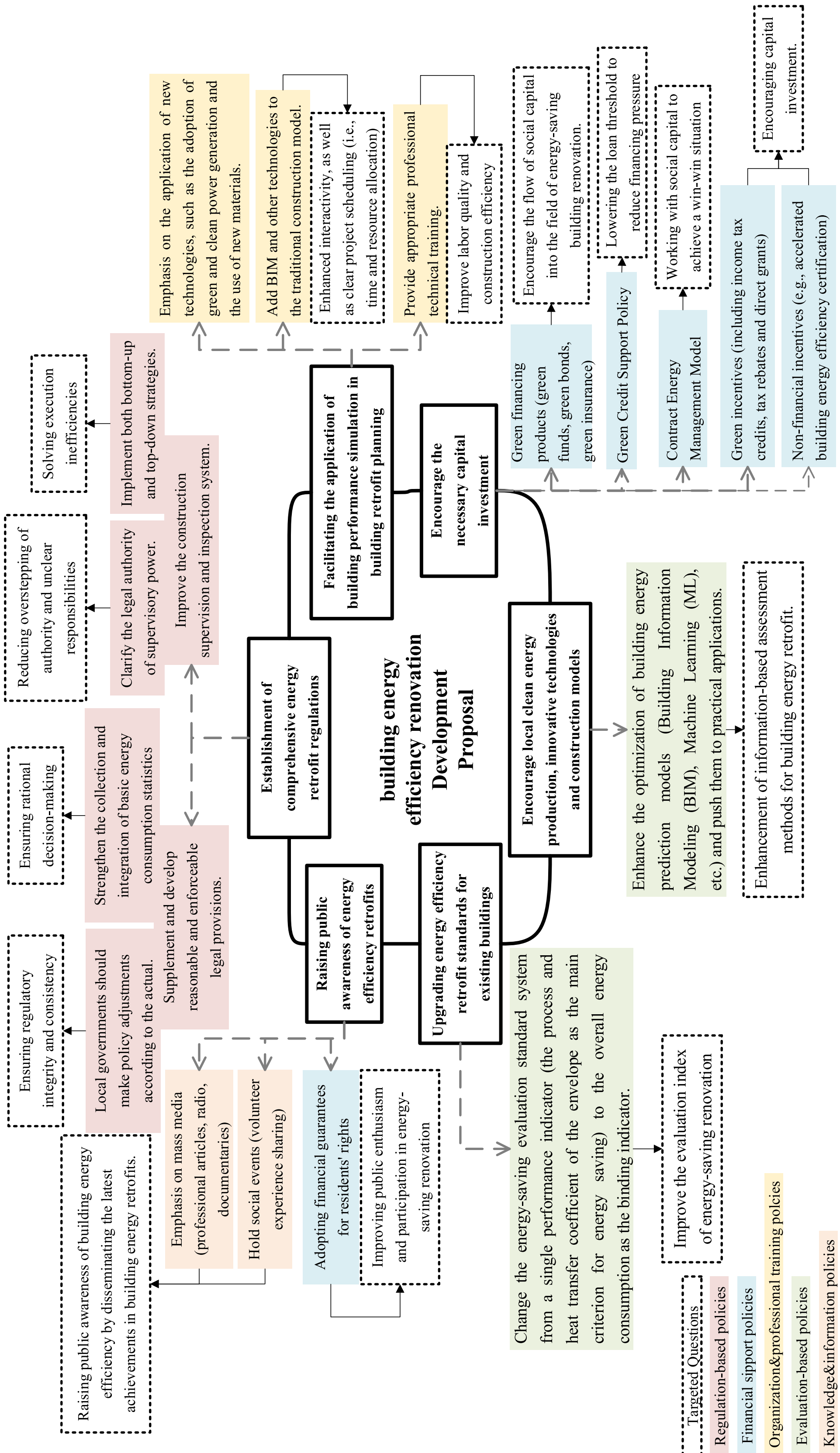

Fig. 9. The implementation roadmap of building energy efficient retrofit policies.

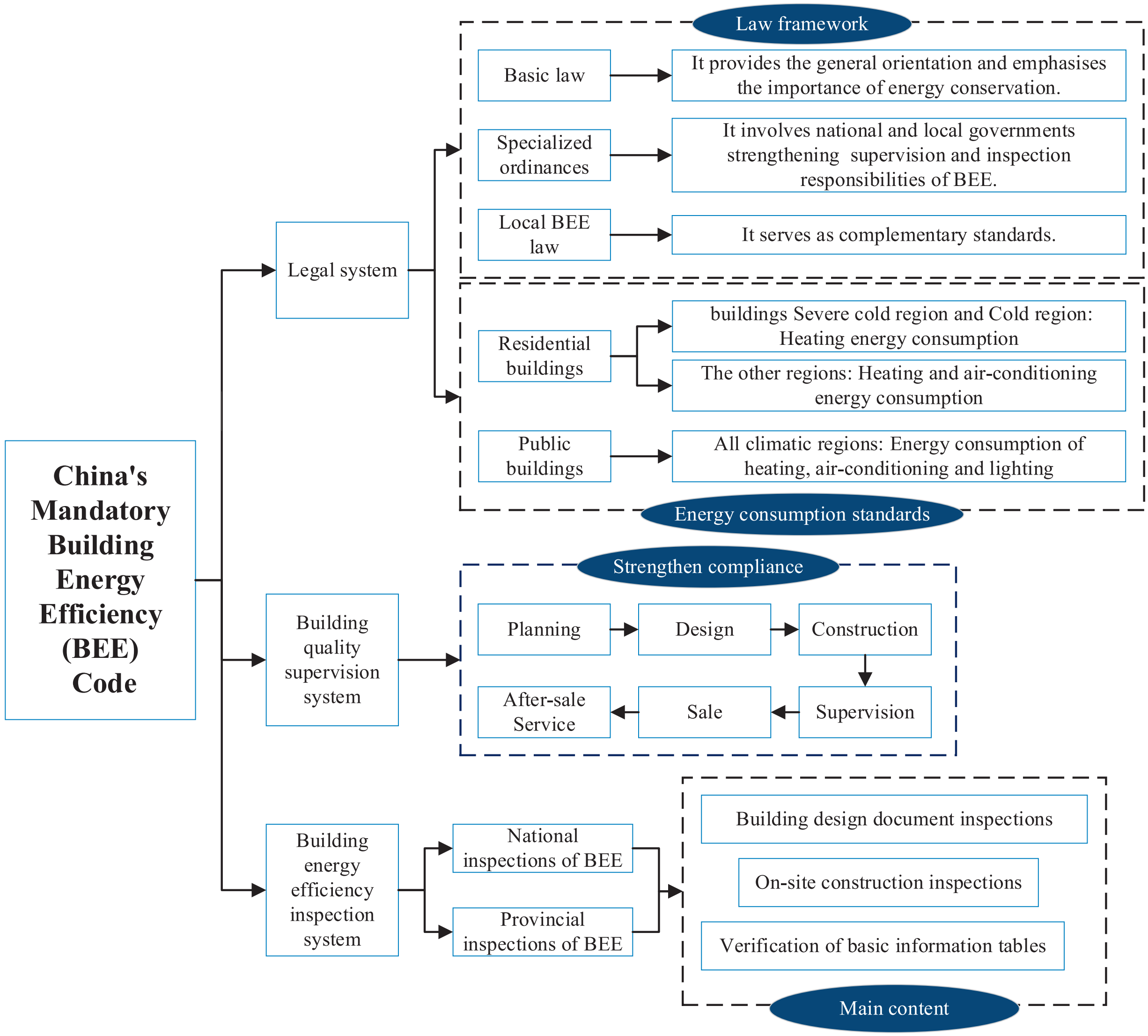

Fig. 10. Framework of existing building energy efficiency regulations in China [158].

renovation is a long-term solution to decrease the financial burden. It is important to encourage green financing in the form of green bonds [180], and green credit support policies [181] that lower the loan threshold to decrease the pressure on project financing, where the availability of loans based on credit scores can avoid some of the financial barriers. In addition, establishing win–win models with social capital to effectively leverage private and public sector capital, such as the contract energy management model explored in the various building energy retrofit pilots mentioned in Section 5. Meanwhile, it is essential to strengthen green incentives (including income tax credits, rebates, and direct grants) and non-financial incentives (e.g., technical assistance for green building financing, accelerated building energy efficiency certification) [178]. Furthermore, green regulations and regulation serve as important safeguards for market-based financing, with the former reducing the negative impact of marginal local political risk on energy efficiency investments while the latter acting as a moderator in strengthening the incentive-investment relationship.

7.6. Incentivizing local clean energy generation, innovative technologies and construction models

New technical measures for energy-efficient renovation of buildings are still limited at this stage in China [33], and there is a particularly strong reliance on the usage of traditional energy and materials. Meanwhile, traditional Chinese construction models, including the Design-Build (DB) model [182] and others, suffer from barriers such as lack of comprehensive consulting services and information about resource availability. Based on the deficiencies of technology in the field of building energy retrofit, many researchers have conducted studies on this issue. In terms of energy applications, Ma et al. [153] divided building energy efficient renovation into three categories: supply-side management (including electrical system retrofitting and the use of renewable energy systems), demand-side management (mainly focusing on energy-saving equipment and low-energy-consumption technologies to reduce heating and cooling demands in buildings), and energy consumption patterns (i.e., products serving project goals and client needs, such as retrofitting building fabric, building services systems, and metering systems). Although there is a detailed classification of energy-saving measures in building energy efficient renovation, a mature operation and maintenance mode and scientific management approach have not yet been established. Therefore, it is necessary to fully reference important research applied in the building industry and urban development process to provide guidance for further improving the efficiency and quality of building energy efficient renovation. For instance, Jia et al. [183] built a building information modeling (BIM) application system based on the Design-Bid-Build (DBB) model covering the schematic design, detailed design, and other phases to cope with the acceptability of project changes and anticipate various uncertainties. With regard to optimizing site layout and project scheduling, Chatzimichailidou et al. [184] demonstrated that BIM technology may detect hazard factors and scenarios in modular construction and simulate material flow to address delays. Therefore, energy-saving measures in building retrofitting also need to fully consider the combination of technologies for energy reduction and decarbonization, as well as new construction and operation modes and dynamic intelligent management, especially by integrating “Artificial Intelligence + Internet of Things + 5G” technologies [185].

7.7. Learning from the advanced initiatives of other countries or regions

Renovating public and private buildings is an essential undertaking, and the European Green Deal has identified it as a key measure to drive energy efficiency and achieve goals in this industry. In 2020, the European Commission unveiled the groundbreaking strategy titled “A Renovation Wave for Europe -Greening our buildings, creating jobs, improving lives” [186]. This strategic initiative was devised to bolster renovation efforts across the EU by doubling annual energy renovation rates within the coming decade. By significantly reducing emissions, these renovations not only contribute to environmental sustainability but also enhance the overall quality of life for individuals residing in and utilizing these buildings. Furthermore, the implementation of these renovation projects is expected to generate a multitude of additional employment opportunities within the burgeoning green construction sector.

Some European countries have consistently held a leading position in the field of building energy-efficient renovation, having introduced numerous policy documents and accumulated extensive practical experience [187,188]. These advanced experiences are highly valuable for the relevant departments of the Chinese government to learn from and reference. For instance, REHVA GB No.32: “Energy Efficient Renovation of Existing Buildings for HVAC professionals” is a guide published by the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) [189]. It provides detailed principles and guidelines for HVAC system design in energy-efficient renovation projects. This includes the selection of efficient air conditioning units, fans, heat exchangers, and other energy-saving equipment, as well as strategies and methods for temperature control, airflow adjustment, timing control, and intelligent control. The guide also covers energy consumption calculation, performance assessment, and building energy rating evaluation tools. Apart from REHVA GB No.32, there are other notable standards in energy-efficient building renovation in Europe. These include EN 15232: “Energy Performance of Buildings - Impact of Building Automation, Controls and Building Management,” which addresses the influence of building automation, control systems, and building management on energy efficiency [190]. These standards and guidelines can assist professionals in the construction industry in accurately evaluating energy efficiency and designing systems for building renovation. They have already been widely adopted in the European construction sector and can provide valuable practical experience and references for the smooth progress and implementation of energy-efficient building renovation in China.

In summary, technology and construction modes of building energy retrofitting are effective approaches to decrease carbon emissions and improve the effectiveness of the retrofitting process. From the perspective of increasing “hard power”, enterprises can adopt green and clean power generation (including wind power, and photovoltaic power, etc.), and use other green alternatives to building materials or upgrade traditional materials in the manufacturing process [191] to promote sustainable green building retrofitting. In addition, it is necessary for enterprises to add predictive models to the traditional construction project management environment to enhance interactive functions [192], to combine historical information and expert opinions to determine the optimal duration in a multi-modal activity network [193], and to sufficiently consider the rational allocation of resources to enable project scheduling in a realistic and complex environment [194]. From the perspective of increasing “soft power” enterprises need to improve the quality of their workforce through technical education and training of construction workers [195], and to enhance market acceptance by disseminating new materials, technologies, and construction models for energy efficiency retrofitting through good communication channels such as seminars and media [196].

8. Conclusions and future studies

This study provides a comprehensive integrated review on policy initiatives of China’s building energy-efficient renovation in terms of policy evolution, demonstration pilots, implementation barrier analysis, and targeted recommendations, and its main findings are as follows: i) Chinese governments at all levels constantly update policies related to building energy retrofitting, with various measures supporting and influencing each other. The regional policies show significant differences due to climate zoning, productivity, and economic conditions, while local policies are the dismantling of central policies in terms of objectives, methodologies, and inheritance of ideas, and in turn, the central government will incorporate successful local experiences into its policy system. ii) The national government selected Shanghai, Tianjin, Shenzhen, and Chongqing Cities as the first batch of pilot cities for building energy efficiency retrofitting, later supplemented by Jinan, Qingdao and other second batch of exemplary cities, the results such as the contract energy management model can provide a practical template for the development of building energy efficiency retrofit and related industries in other regions. iii) The barriers to the existence of building energy efficiency retrofit policies are divided into four levels from the perspective of stakeholders: governments, householders, enterprises and research institutions. It deeply explores the challenges such as the scientificity, continuity and targeting of policy decisions weakened due to the lack of basic energy consumption data, the lack of valuing the quality of retrofitting, the short cycle of plan making, and the local governments copying or applying central documents. iv) Based on the current development barriers in the field of building energy-efficient renovation, this paper proposes a blueprint for the corresponding implementation roadmap, and emphasizes on strengthening the collection and integration of energy consumption statistics information to provide the possibility of cross-sector and cross-system cooperation. It also proposes some recommendations to improve the process and regulatory authority of building energy efficiency inspection to effectively address the problems of inefficient law enforcement and unclear responsibilities, and these feasible suggestions will provide valuable references for the improvement of existing policies.

This paper analyzes the temporal and spatial development of building energy retrofit policies in China at this stage, and clearly identifies the policy barriers that exist for each stakeholder, providing theoretical support for subsequent governments at all levels to improve and optimize legal standards and corresponding policy norms. However, the limitations of this study cannot be ignored, mainly including: searching for national and provincial related building energy retrofit policies is mainly conducted through official government websites and journal papers at all levels, while local websites suffer from untimely updates and weak relevance of ponderous information, and there are inevitable problems of missing content and incomplete information when the policies are sorted out. During the process of checking policy information, this paper takes the national policy as the main line, not limited to the official websites of housing and urban construction departments to search, and the mainstream media (e.g., People’s Daily Online, Xinhua Online, and Zhongxin Online) and Chinese journals to organize the policy documents, in order to ensure the accuracy and completeness of the policy documents as much as possible.

The scientific governmental decision-making of building energy-efficient renovation is the prerequisite and core of its renovation management aspects and renovation behavior, while the research trend analysis in Section 3 reveals that the related studies on policy decision-making are in the initial stage. Future studies are necessary to establish a real-time database and dataset partitioning of the existing building stock and energy consumption, and introduce the decision support system based on a data-driven approach to assist decision makers in selecting better retrofit measures for the actual building energy environment. Based on the plan-implement-check-act cycle, an "adaptive" policy model can be developed and applied to quantitatively assess the performance targets of specific building retrofit policies, and to supplement and improve the next stage of the program to address the complicated changes in new technologies, knowledge, and environments.

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

No data was used for the research described in the article.

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