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Investigation of policy tools for energy efficiency improvement in public buildings in China—current situation, obstacles, and solutions

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Abstract

The energy consumption from the building sector accounts for more than 21% of the total in China, where the energy-use intensity of public buildings could reach 3 times that of residential buildings. Energy efficiency improvement (EEI) is considered to be one of the most rapid and cost-effective means for the building sector to achieve carbon neutrality. The Chinese government has carried out a series of policy tool exploration to promote the energy efficiency improvement efforts by public building owners since over a decade ago, but encountered various problems and obstacles. This paper investigated and compared the current status challenges, and problems in the implementation of EEI policy tools in China and developed countries through literature review, field investigations and interviews with experts and stakeholders, and finally also put forward some possible coping strategies for Chinese government. Results indicated that energy grading and labeling, energy benchmarking, carbon-emission trading and energy-consumption quota management were the main 4 EEI policy tools designed based on measured energy consumption data, where the first 3 ones had been widely used over the developed countries but the last one was unique to China. Difficulty in large-scale collection of building energy-consumption data, lack of scientific methods on building energy-use level evaluation, limited data application and feedback, undesirable association between stakeholders, etc., were the main obstacles for achieving the long-term effectiveness of the EEI policy tools. Cooperating with energy supply enterprises to collect data, establishing an effective energy grading system and a closed loop of policy implementation, exploring a new model of building carbon-emission trading and a differential pricing mechanism, combined with innovative financial supports, might be the solutions. The main contribution of this study is that a comprehensive investigation and analysis on the current development status, obstacles, and possible solutions of the public building EEI policy tools in China was carried out, which is expected to provide a reference for the government of China and even the world.

Keywords: Energy grading and labeling, Data collection and disclosure, Carbon-emission trading, Differential electricity pricing

Introduction

In China, the operation energy consumption and carbon emissions from the building sector both account for as high as more than 21% in the total society value, with a growth rate higher than 9% year by year in the past 20 years which has exceeded the growth rate of the building area (Building Energy Research Center of Tsinghua University 2022). Therefore, the building sector has become one of the core areas of China's carbon emission reduction action plan after President Xi Jinping promised the world the goal of "carbon peak by 2030 and carbon neutrality by 2060" in September 2020. Since the energy consumption and carbon emission intensity of public buildings can reach 3 times that of residential buildings (Building Energy Research Center of Tsinghua University 2022), it is one of the core objects of all cities in developing policies and paths of energy-saving and carbon-emission reduction in the building sector. The report "Energy Efficiency 2021" from the International Energy Agency (IEA) (International Energy Agency 2021) noted that energy efficiency improvement is one of the most rapid and most cost-effective means to achieve carbon neutrality in the building sector. Some of China's recent roadmaps, such as "Action Plan for Carbon Peak by 2030", also pictured energy efficiency improvement (EEI) as an important path to achieving carbon peak and carbon neutrality in the building sector (Council and of China. Action Plan for Carbon Peak by 2030).

In fact, China has begun EEI efforts since the early 1980s by an energy-efficiency design standard for residential buildings in the very cold and cold zones of the country (Feng et al. 2009), and then developed the first energy-efficiency design standard for public buildings in 2005 (Ministry of Housing and Urban–Rural Development 2005). After that, the Chinese national government and local governments have explored a series of policy tools to control the energy intensity of public buildings, as is shown in Table 1. Among all the tools, energy-related standard is used the most, including energy-efficiency design standards, retrofitting technical codes, assessment standards for green building and low-energy building, energy-consumption or energy-consumption quota standards, covering the design and operation stages of the building. Meanwhile, the Chinese government has tried to launch the pilot projects in several provinces and cities including the construction of provincial or city-level public building energy consumption monitoring systems, energy efficiency evaluation and grading, and building carbon emission trading. In addition, provincial and city-level governments have been continuously introducing relevant financial incentive policies to promote the energy efficiency of public buildings. However, despite some energy-saving achievements in some provinces and cities (for example, Shanghai and Beijing have both reported the slow decline trend of energy intensity in public buildings in recent years (Commission and of Housing and Urban–Rural Development. Monitoring and analysis report of energy consumption in office buildings and large public buildings in Shanghai. 2021)), the overall energy-use intensity (EUI) of public buildings in China continues to grow these years, as is shown in Fig. 1 (Zhou et al. 2022a). The EUI of public buildings has increased nearly a quarter from 20.3 kgce/m^2 in 2010 to 25.1 kgce/m^2 in 2019, and there was a small decline in 2020 due to the outbreak of COVID-19. The increase of the amount of large-scale premium commercial buildings with central air conditioning with the development of China's economy may partly account for the growth of EUI of public buildings, while the lack of effective and operational EEI policy tools may be the other reason. The biggest challenge

Table 1 The Chinese government's EFI efforts on public buildings

Policy tool	Name of the document	EEI scheme	Target stage	Application scope
Design standard	Design standard for energy efficiency of public buildings (2005 (Ministry of Housing and Urban–Rural Development 2005), and 2015 (Ministry of Housing and Urban–Rural Development 2015a)); General code for energy efficiency and renewable energy application in buildings (2021 (Ministry of Housing and Urban–Rural Development 2015b))	The standards promoted the EEI of the energy-use system by continuously strengthening the thermal performance of the envelope, the performance coefficient (COP) of the equipment system, and the utilization of natural cold and heat sources and renewable energy in the building design process. Whether a building has complied with the design standards will be specifically checked before its final acceptance	Design	Nationwide (Some cities also issued localized documents)
Technical code for retrofitting	Technical code for the retrofitting of public building on energy efficiency (2009 (Ministry of Housing and Urban–Rural Development 2009), and now is being revised)	The codes stipulated the standardized processes of energy-saving retrofitting of public buildings, gives suggestions on the technical list of energy-saving retrofitting technologies, and clarifies the requirements for the implementation effect after retrofitting	Operation	Nationwide (Some cities also issued localized documents)
Assessment standard	Assessment standard for green building (2006 (Ministry of Housing and Urban–Rural Development 2006), 2014 (Ministry of Housing and Urban–Rural Development 2014), and 2019 (Ministry of Housing and Urban–Rural Development 2019a)); Technical standard for nearly zero energy buildings (2019 (Ministry of Housing and Urban–Rural Development 2019b)); Assessment standard for green retrofitting of existing building (2015 (Ministry of Housing and Urban–Rural Development 2015c))	Through the certification mechanisms of green building, near-zero energy building, and green retrofitted building, the energy efficiency performance of newly constructed or existing buildings could be evaluated and compared with the benchmarking buildings. The higher the energy efficient performance is, the higher the certification grade is, and higher grades will have a positive impact on rental and sale prices, application for government financial subsidies, and corporate reputation etc., which could be an incentive of EEI	Design and operation	Nationwide (Some cities also issued localized documents)

Table 1 (continued)

Policy tool	Name of the document	EEI scheme	Target stage	Application scope
Energy consumption standard	Standard for energy consumption of building (2016 (Ministry of Housing and Urban–Rural Development 2016))	The standard specified the constraint and leading value of heating and non-heating energy consumption indicators for office, shopping mall and hotel buildings in each climate zone, so as to provide a reference for the energy-saving operation, energy consumption management and energy efficiency improvement of buildings	Operation	Nationwide (Some cities also issued localized documents)
Energy consumption quota standard and management	Energy consumption quota standard for public institutions issued by the government of Sichuan, Hainan, and Shanxi, etc. (Administration for Market Regulation of Sichuan Province. Energy consumption quota standard for public institutions DB51, T 2762-2021. 2021); Interim regulations on power consumption quota management of public buildings in Beijing (2014 (Commission and of Housing and Urban–Rural Development. Interim regulations on power consumption quota management of public buildings in Beijing 2014), and 2019 (Commission and of Housing and Urban–Rural Development. Interim regulations on power consumption quota management of public buildings in Beijing 2020))	The standards set the upper limits of annual operating energy consumption for the public institutions and public buildings as a reference for the government and building owners to carry out the building energy conservation management work. Only Beijing directly used the power consumption quotas to annually assess the energy use of public buildings, and any building that consumed the more energy than its quota, would be forced to conduct energy audits, energy-saving retrofitting or be fined	Operation	Some provinces and cities
Energy consumption monitoring	The implementation opinions on strengthening the management of energy conservation in office buildings of state organs and large public buildings (2007 (Ministry of Housing and Urban–Rural Development Ministry of Finance of the People's Republic of China. The implementation opinions on strengthening the management of energy conservation in office buildings of state organs and large public buildings 2007))	The document called for the local governments to build provincial or city-level energy consumption monitoring systems and platforms for state organs office buildings and large public buildings (larger than 2 0,000 m^2). A total of 18 provinces and cities have participated in the pilot project since 2007, including Beijing, Tianjin, Shenzhen, Hebei, Liaoning, etc.. In this project, all the costs of the building energy consumption monitoring devices and the city-level platform construction are mainly borne by the local governments, with a small part subsidized by the state	Operation	Piloted in 18 provinces or cities since 2007

Table 1 (continued)

Policy tool	Name of the document	EEI scheme	Target stage	Application scope
Energy efficiency evaluation and grading	Notice on the trial implementation of the energy efficiency evaluation and grading system for civil buildings (2008 (Ministry of Housing and Urban–Rural Development. Notice on the trial implementation of the energy efficiency evaluation and grading system for civil buildings 2008))	The document required that the newly constructed (or rebuilt or expanded) state organs office buildings, large public buildings, (ultra-) low-energy consumption buildings should be subjected to an energy efficiency examination and evaluation after completion, and would be issued an energy efficiency grading label according to the theoretical value. The label could be updated after the building project had operated for one year and obtained the measured energy efficiency. A total of 18 provinces and cities have participated in the pilot project since 2008, including Beijing, Tianjin, Shanghai, Chongqing, Jiangsu, Zhejiang, etc.	Design and operation	Piloted in 18 provinces or cities since 2008
Carbon emission trading	Notice on launching the pilot work of carbon emission right trading (2011 (Development et al. 2011)); Building energy conservation regulations of Tian Jin (2012 and 2018 (Standing Committee of the Tianjin Municipal People's Congress. Building energy conservation regulations of Tian Jin 2020)); Interim measures on the administration of carbon emission rights trading in Shenzhen (2014 (Shenzhen Government. Interim measures on the administration of carbon emission rights trading in Shenzhen 2014))	Buildings could obtain surplus carbon-emission quotas by EEI from energy-saving operation or retrofitting, and then profit by selling these surplus quotas to buildings with insufficient quotas through the carbon trading market. The Chinese government approved 7 provinces and cities, including Shanghai, Beijing, Guangdong, Shenzhen, Tianjin, Hubei and Chongqing, to carry out the pilot carbon emission trading rights in 2011, and officially launched the pilot carbon trading market in 2013. Subsequently, Tianjin and Shenzhen respectively issued documents to include large public buildings into the trading entities in the carbon trading market	Operation	Piloted in Shenzhen and Tianjin since 2011

Table 1 (continued)

Policy tool	Name of the document	EEI scheme	Target stage	Application scope
Financial incentives	The implementation opinions on accelerating the development of green buildings in China (2012 (Ministry of Finance of the People's Republic of China Ministry of Housing and Urban–Rural Development. The implementation opinions on accelerating the development of green buildings in 2012))	The document advocated the establishment of a high-star financial policy incentive mechanism for green buildings, which would provide financial subsidies or floor area ratio rewards for buildings that obtain green building certification labels. The higher the green level was, the more the amount of rewards would be. Many provinces and cities have issued a series of specific reward programs since 2012, and the reward amount ranged from 5 CNY/m^2 to 100 CNY/m^2	Design and operation	Nationwide (Many cities also issued localized documents)
	Several measures to support the development of the ultra-low-energy construction industry (2022 (Department of Industry and Information Technology of Heilongjiang Province. Several measures to support the development of the ultra-low-energy construction industry 2022))	The government gave financial incentives to buildings that obtain the certification of ultra-low, nearly zero or zero energy consumption building. The lower the energy consumption was, the higher the reward amount would be. Many other provinces or cities, such as Beijing, Chongqing and Shenzhen, have issued similar documents, and the reward amount ranged from 30 CNY/m^2 to 1000 CNY/m^2	Design and operation	Many provinces and cities
	Interim measures for the management of energy-saving and green retrofitting public buildings and incentive funds (2017 (Commission and of Housing and Urban–Rural Development. Interim measures for the management of energy-saving and green retrofitting public buildings and incentive funds 2017))	The government gave certain financial subsidies to the buildings that had carried out energy saving retrofitting with the energy-saving rate higher than 15%. Many other provinces or cities, such as Shanghai, Chongqing, Shenzhen and Jinan, have issued similar documents, and the reward amount ranged from 10 CNY/m^2 ~ 1000 CNY/m^2	Operation	Many provinces and cities

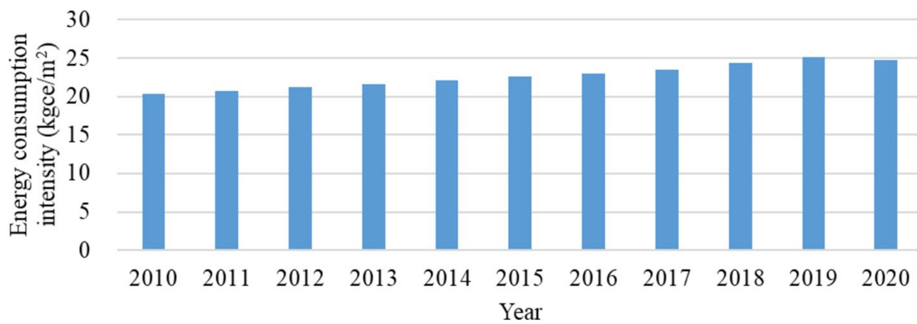


Fig. 1 The energy consumption intensity of public building from 2010 to 2020 (Zhou et al. 2022a)

of energy-related standards is the difficulty in continuously tracking the implementation of the requirements from the standards, while the pilot projects and financial incentives often requires sustained government investment which had difficulty in sustainability.

Based on the team's previous long-term support work in the government department, the following problems could be found in the implementation of the public building EFI policies:

1) The government departments often promote these policies with great enthusiasm, while the building owners is not motivated to participate, and even think that these policies have increased the burden on them.
2) The implementation of these policies is too dependent on the governments' supervision and financial subsidies which has result in heavy burden on the government, although the incentives are far from compensating for the building owners' investment in energy efficiency improvement.
3) Some of the policies were not initially designed to fully take into account the actual possible obstacles, resulting in poor sustainability and a waste of government time and finance.

Therefore, in order to analyze the causes and find out the possible solutions of the above problems, the study compared in details the current status of EEI policy tools developed in China and abroad through literature review, and analyzed the problems, challenges and reasons why the existing EEI tools in China had difficulty in raising the motivation of public building owners to improve the energy efficiency based on the field investigations in 29 green and 30 traditional public buildings and face-to-face interviews with the domain experts, governmental personnel, building owners, operation team and users. As the actual operation energy consumption is the most direct indicator to test whether the building is really energy-saving with high energy efficiency, and practical effect-oriented EEI policy design is being a trend of the Chinese government, the subject of this study focused on the EEI policy tools right based on actual operational energy consumption data. The objective of this study is to put forward the development suggestions on EEI policy tools, so as to provide the government a reference for the design of energy and carbon-emission controlling policies in public buildings in China and even the world.

Methodology

Scientific policy design and decision-making usually requires a more in-depth and comprehensive understanding of policies, including the understanding of the latest development and new trends of the related policies both at home and abroad, as well as the understanding of the action mechanism and implementation effect of each policy. Therefore, the study divided the content into 3 tasks, as is shown in Fig. 2, namely, review and comparison of the EEI policy tools at home and abroad (Task 1), analysis of problems and related-reasons of EEI policy tools in China (Task 2), and design of possible coping strategies and preliminary case analysis (Task 3).

The core task of Task 1 is to review and compare the global development status and trend of typical EEI policy tools based on actual operational energy consumption data, and relevant explorations in China. The method of literature and typical case review were used, where the literature review was carried out by searching from the academic journal paper database (such as "the Web of science" and "Google Scholar") through keywords ("public building &, energy efficiency & improvement or energy saving"), and the typical case review was conducted mainly through consulting the EEI related policy materials and research reports on public buildings issued by the governments of typical provinces or cities at home and abroad. The international cases were mainly from C40 Cities Climate Leadership Group, including the cities from US, EU, Japan, South Korea, etc., and the domestic cases were mainly from the pilot provinces or cities in the policies listed in Table 1, including Beijing, Shanghai, Shenzhen, Chongqing, etc..

The core task of Task 2 is to summarize and discuss the problems and possible causes of EEI policy tools in the implementation process through comparative analysis of the domestic and foreign cases. A policy tool often involves several stakeholders from its design to implementation, and whether it can really promote EEI mainly depends on the building owners' understanding and acceptance degree on the policy as well the trade-off between the benefits of policy implementation and the risk in investment, business secret and reputation. Therefore, the study took Beijing (the capital city of China) as an example, and carried out field investigation in 29 green public buildings (Zhou et al. 2022b) and 41 traditional public buildings in Beijing in 2020 and 2022, respectively. The completion time of the buildings ranged from 1981 to 2020, and the functional types of office (51 samples), mall (7 samples) and hotel (5 samples) account for 90% of the total samples. In each investigation, the team invited government officials and domain experts to conduct face-to-face interviews with the building owners, operation teams and users,

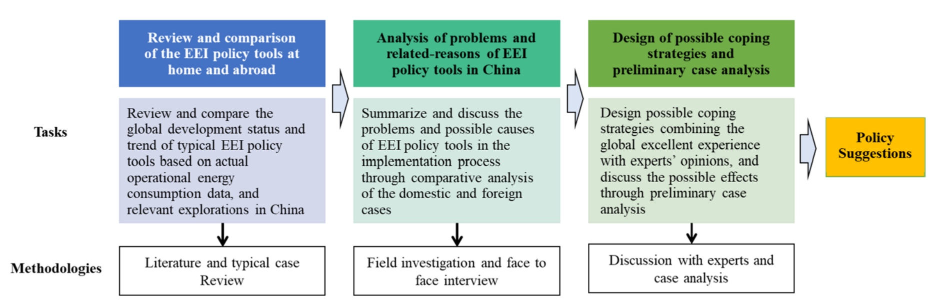


Fig. 2 Tasks and methodologies of the study

discussing about the difficulties in policy implementation, energy-saving operation and management measures, user satisfaction and the demands for EEI policies, as is shown in Fig. 3. A total of nearly 350 people participated in the field investigations and face-to-face interviews. The problems and possible causes were finally summarized from the investigations.

The core task of Task 3 is to design possible coping strategies combining the global excellent experience with experts' opinions, and discuss the possible effects through preliminary case analysis. Based on the advanced experiences summarized in Task 1 and the problems found in Task 2, the team promoted some optimization suggestions for EEI policy tools with some preliminary case analysis and verification. At the same time, the team invited several times the personnel from local government departments of pilot provinces and cities and the experts who have provided long-term support on EEI policy decision for the local government to discuss the promoted suggestions through on-site and online meetings, so as to optimize the suggestions and further improve their applicability and operability as much as possible.

Results

Review and comparison of the EEI policy tools at home and abroad

According the result of literature and case typical case review, the global building EEI policy tools could be divided into 3 categories according to the strength of the government-led efforts, namely, mandatory type, voluntary type and incentive type. From the perspective of specific measures, they could be further divided into 11 sub-categories ((Takagi et al. 2015; Trencher et al. 2016)), namely, 1) mandatory type (6 sub-categories): energy-efficiency related standards, energy grading and labeling, energy benchmarking, periodical energy efficiency auditing or retro-commissioning, carbon-emission trading, and government leadership; 2) voluntary type (2 sub-categories), awareness raising programmes, and voluntary leadership prgrammes; and 3) incentive type (3 sub-categories): financial incentives, non-financial incentives, and promoting green leasing.

As the actual operation energy consumption is the most direct index to evaluate whether a building is really energy saving, and the Chinese government is also seeking the practical effect-oriented EEI policy tools, the study focused on the analysis and comparison of 4 widely used EEI policy tools which were designed based on actual

Fig. 3 Field investigation and face-to-face interview: **a** on-site photo, and **b** investigation outline

operational energy consumption data, including energy grading and labeling, energy benchmarking, carbon-emission trading, and energy-consumption quota management.

Building energy grading and labeling

Building energy grading and labeling (BEGL) is the earliest and most widely used EEI tool in the world, which uses continuous or discontinuous performance grade indicators (e.g. color blocks) to mark the actual energy intensity or energy efficiency of the building. It has been implemented in more than 40 countries and regions, including the US, the EU, Japan and South Korea, etc., and some typical cases from different countries are presented in Fig. 4.

Table 2 listed the target group, grading basis and scheme, main promotion strategies, and achievement of the BEGL tools in different countries, and the following similarities and differences could be found:

1) EEEG in China focuses on only a very few buildings with great demonstration effect or with excellent design performance, including newly constructed (or rebuilt or

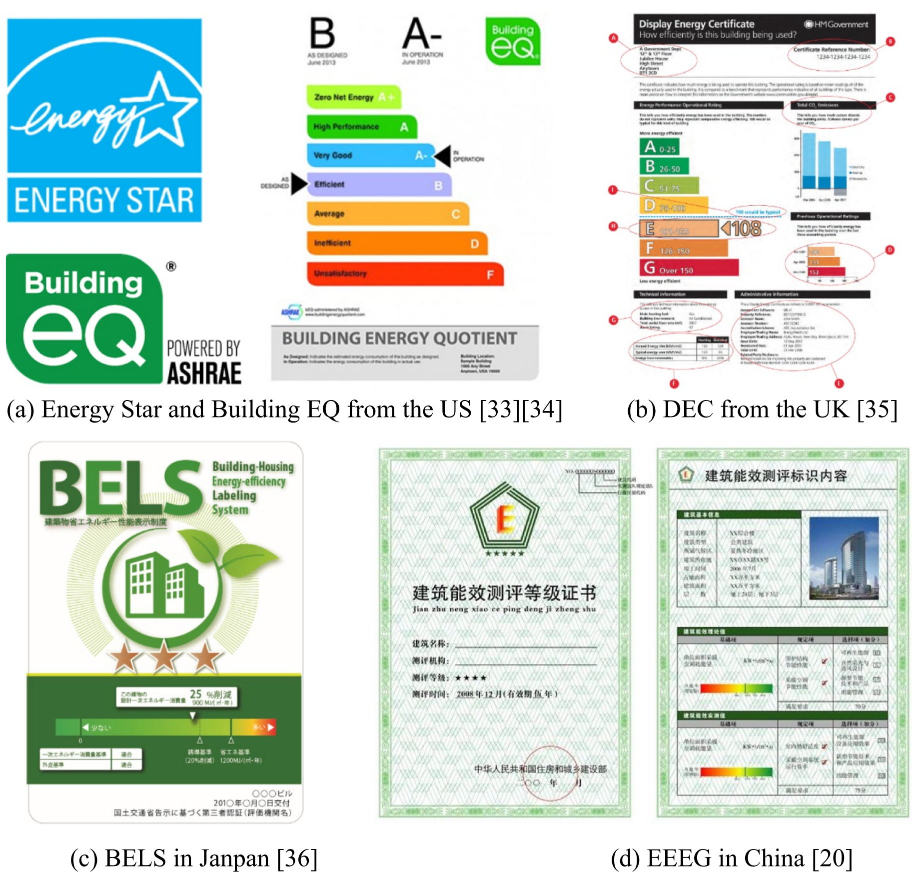


Fig. 4 Energy grading and labeling tools. **a** Energy Star and Building EQ from the US ((Agency and History of EPA's Climate Partnership Programs. 2022; ASHRAE. Building E.Q. 2022)). **b** DEC from the UK (Department of Finance. Display Energy Certificates 2022). **c** BELS in Janpan (Center and of Japan. BELS evaluation. 2022). **d** EEEG in China (Ministry of Housing and Urban–Rural Development. Notice on the trial implementation of the energy efficiency evaluation and grading system for civil buildings 2008)

Table 2 Building Energy Grading and Labeling in different countries

Country and Tool	Introduced Year and Target Group	Grading Basis	Grading Scheme	Main Promotion Strategies	Achievement
US, Energy Star and Building eQ	1998, Commercial and residential buildings	Measured energy use intensity (EUI)	Each building receives a score ranging from 1 to 100 points, where 50 points represents the average level of EUI. If the score is more than 75 points, the building will be certified with an "Energy Star" label, indicating that the building is worth learning in energy-saving, while a score of 50–75 indicates that improved operation and maintenance could save energy for the building, and a score of 0–50 means that the building has great potential for energy saving and needs to make efforts on EEI (Agency and Star 2022) Besides, ASHRAE also developed another BEGL tool called Building Energy Quotient (Building eQ) and rated the buildings into 7 grades where Grade C represented the average level (ASHRAE. Building E.Q. 2022)	The US government has required federal agencies to rent Energy Star-certified buildings for office space since December 2010, and the building owners could use the score and label to apply for a loan discount from the government	More than 38,000 commercial buildings so far have been certified with "Energy Star" labels, and about 230 billion kWh of electricity were saved just 2019 alone (Agency and History of EPA's Climate Partnership Programs. 2022) A total of 1,042 buildings was reported to have derive a "Building EQ" by the January, 2018 (ASHRAE. Building E.Q. 2022)
UK, Operational Ratings and Display Energy Certificates (DEC)	2009, Public buildings with a total effective building area greater than 250 m^2	Measured energy use intensity (EUI)	"DEC" compares the building's EUI with a standardized benchmark EUI (represents the average level), and then gives the building a score (the score of the benchmark EUI is 100 points). The building will be divided into 7 grades from A to G according to its score, where 100 points is the cut-off point of Grade D and E (Department of Finance. Display Energy Certificates 2022)	The UK legislation (CIBSE TM27: 2009) requires that all the public buildings could not be sold or rented without a "DEC" label and should reach Grade C by 2030	By the end of 2019, 96% of the total number of registered properties in the UK have derived "DEC" labels (Department of Finance. Display Energy Certificates 2022)

Table 2 (continued)

Country and Tool	Introduced Year and Target Group	Grading Basis	Grading Scheme	Main Promotion Strategies	Achievement
Japan, Building-housing Energy-efficiency Labeling System (BELS)	2014, New or converted residential and public buildings	Design based calculated energy saving rate (ESR)	"BELS" compares the building's design or measured primary-energy consumption (PEC) with a benchmark value, and then rates the building into 5 grades from 1 to 5 stars according the reduction rate of the building's PEC relative to the benchmark value (Center and of Japan. BELS evaluation. 2022)	Buildings are not mandatory to participate in the BELS grading and labeling, but the Japanese government takes the "BELS" certification as a prerequisite for applying financial incentives and zero-energy-building related subsidies	A total of 3,278 public buildings have derived the "BELS" certification till the end of November 2022 (Residential Performance Evaluation and Certification Association 2022)
China, Energy Efficiency Evaluation and Grading (EEEG)	2008, newly constructed (or rebuilt or expanded) state organs office buildings, large public buildings (greater than 20,000 m^2), (ultra-) low-energy consumption buildings	Design based energy saving rate (ESR)	"EEEG" gave a EEEG grade to a building according to its designed or calculated energy-saving rate relative to a reference building and its implementation efforts on the mandatory energy-saving measures, and the grade could not be changed even after the building had been operated for one year and obtained the measured energy consumption or efficiency (although the measured values could be written into the label)	The Chinese government forces that the buildings within target group should be subjected to an energy efficiency examination and evaluation after completion, and would be issued an energy efficiency grading la according to the designed or calculated EUI (Ministry of Housing and Urban–Rural Development. Notice on the trial implementation of the energy efficiency evaluation and grading system for civil buildings 2008)	By far, only 377 public buildings have derived "EEEG" certification, and all of certifications represents a designed energy-saving performance rather than the actual energy-consumption level

expanded) state organs office buildings, large public buildings (greater than 20,000 m^2), and (ultra-) low-energy consumption residential and public buildings, which might account for no more than 5% in the annual total newly constructed (or rebuilt or expanded) buildings in China, while the BEGL tools in the other 3 countries cover almost 100% of the residential and/or public buildings.

2) Both the BEGL tools in China and Japan use the design based calculated energy saving rate (ESR) rather than the measured energy use intensity (EUI) used by the US and UK as the grading basis. As a result, both China and Japan have set the number of grading levels as 5, namely from 1 to 5 stars, where 1 star is the minimum threshold requirement for the design of a new building, while the US and UK set 7 grading levels, where the middle one always represents the local average EUI level.

Compared with using measured EUI as the grading basis, the advantage of using calculated ESR is that the building performance could be graded and labeled early at the design stage, while the disadvantage is that the calculation process of ESR requires the specification of a standard building model for comparison, which is usually complex and cost-consuming. What's more, the obtained labels based on calculated ESR more represent the design energy efficient of the building's body rather than the actual energy-use level of the building in the operation stage, and so could not be used as a basis to judge whether the building needs to carry out energy-saving renovation just like Energy Star and DEC do.

3) Governments in China, the US and UK all forces specific function or types of buildings to participate in BEGL, while only Japanese government encourages but not enforces the buildings' participation. However, all the countries except for China have designed some financial or market economic incentives related to the BEGL certification, which has greatly boosted the popularity of BEGL certification in these countries. For example, the building owners could use the score and label to apply for a loan discount from the government in the US, and the public buildings could not be sold or rented without a "DEC" label in the UK, while the Japanese government takes the "BELS" certification as a prerequisite for applying financial incentives and zero-energy-building related subsidies. On the contrary, EEEG certification in China is very unattractive and more like a burden for the building owners as there is not any economic incentives provided by the government or the market after obtaining the certification but instead the certification process requires a certain cost to hire a third party to carry out the evaluation work. As a result, only 377 public buildings all over the country in China have received the "EEEG" certification in the last 15 years, which is about tenth of the number in Japan and less than one percent of that in the US, as is shown in Table 2.

Energy benchmarking

Energy (consumption) Benchmarking is an EEI policy tool developed in the US in 1990s and now widely used in and outside the US (Park et al. 2016). Energy benchmarking evaluates and analyzes the energy and water consumption data of each public building, compares it with the historical data of the building itself and the data of the same type of buildings in the region, and visualizes the results on the city map (e.g. using color blocks covering on the building model shown in Fig. 5), so as to urge and help the buildings to carry out EEI efforts (Roth et al. 2020). This mechanism greatly improves the transparency of building energy consumption data, provides an energy consumption baseline for public building owners, and can continuously monitor and track the retrofitting effect of buildings.

Currently, more than 10 cities in the US, including New York, San Francisco, Philadelphia, Seattle, etc., and Canada, Singapore and some other countries and regions, are implementing the energy benchmarking programmes. At the beginning, only the participation of large public buildings (e.g., larger than 50,000 square feet in New York, and over 10,000 in San Francisco) in the city's energy benchmarking was mandatory, and small and medium-sized public buildings were gradually covered in the mandatory scope (e.g., larger than 25,000 square feet in New York) (Trencher et al. 2016). The programme provides free and easy-to-use data tools such as generating the buildings' EUIs, continuous monitoring and analysis of energy efficiency, horizontal comparison with the same region and type of buildings, and comparison on different EEI investment or retrofitting schemes for the public buildings, to attract more building owners to voluntarily and continuously submit data to the city's energy benchmarking platform. For example, buildings in the US could use the "ENERGY STAR PortfolioManager" (Agency and Star 2022) which is also the key tool of energy data submission, analysis, and comparison for "Energy Star" certification, to carry out benchmarking.

However, due to the differences in the building energy use characteristics, the amount of buildings participated in the programme, and the intensity of government supervision in different regions, the energy-saving effect brought by Energy Benchmarking also varies from place to place. For example, a total of 3247 properties in New York have taken part in the benchmarking during 2010 and 2021, and the average EUI has lower by 25% from 2010 to 2021 (Office of Climate and Environmental Justice 2021), while 925 public buildings have participated in the benchmarking between 2008 and 2020 in Singapore and the overall EUI has lowered by 21% over the period (National University of Singapore 2021), and the two numbers are respectively 493 and 14% in San Francisco between 2009 and 2019 (San Francisco Public Utilities Commission 2022), and 855 and 5.09% in Philadelphia between 2013 and 2017 (City of Philadelphia Office of Sustainability 2019).

So far, no city in China has implemented city-level building energy benchmarking programmes. The most likely reason is that the data sources and owners in China, including the building owners, government departments and energy suppliers, are all very conservative and reluctant to make its data public for privacy and avoiding penalties from higher government departments. In spite of this, China required that all the buildings over 2,000 square meters should carry out comparison of their measured energy consumption data with similar buildings in the code "General code for building energy conservation and renewable energy utilization" (Ministry of Housing and Urban–Rural Development 2015b) newly issued in April 2022, but the Chinese government has not yet developed a specific implementation plan about the benchmarking.

Fig. 5 Energy benchmarking map of New York (Mayor's Office of Sustainability New York University's Center for Urban Science and Progress. NYC Energy Water Performance Map 2022)

Building carbon-emission trading

Carbon-emission trading (CT) originated in the EU on January 2005, and now 16 regional, national or sub-national CT markets have been built worldwide, but the trading units of most of them are enterprises from industry and public institutions rather than buildings. Building Carbon-emission Trading (BCT) was first implemented in Japan in 2010 (Bureau of Environment. Tokyo Cap and Trade 2022), and has gradually been included in the decision-making scope by local governments in recent years. The items traded in the BCT are the buildings' surplus or short carbon emission quotas. In 2010, Japan launched the BCT programme for large public buildings and the carbon emission reduction report programme for small and medium-sized buildings, and reported 25% and 27% carbon-emission reduction by all the buildings in the market in the two five-year trading period of 2010 to 2014 and 2015 to 2019, respectively (Bureau of Environment. Tokyo Cap and Trade 2022).

China also launched a pilot BCT programme in public buildings in Shenzhen and Tianjin in 2011 (Ministry of Housing and Urban–Rural Development 2008), but no cases about BCT in the two cities have been reported so far. The carbon-emission of each single building is too small and scattered, while the cost of unit carbon-emission reduction is too high when compared with those in the industry sector, which makes it too difficult to promote CT in the building sector. For example, Beijing required that a property should take part in the CT if its annual carbon-emission was equal to or higher than 5,000 tons (People's Government of Beijing Municipal 2022). According to the statistics of building energy consumption data in Beijing (Conservation et al. 2021), an office building about 50,000 m^2 could consume energy about 2,550 tce (calculated according to the average EUI of this type of buildings in Beijing) and emit carbon about 5,100 tCO_2, just reaching the entry threshold of CT market. If the building achieves a 15% energy-saving rate through EEI measures (e.g. retrofitting), then it can save an annual carbon emission quota about 765 tCO_2. However, as the current average CT price is only 50 ~ 80 CNY/tCO_2 in China, the annual income of this building from the trading is just 38,000 ~ 61,000 CNY, less than 0.1% of the renovation cost (about 12.2 CNY/tce averaged from the data of 31 retrofitting offices in Beijing). Therefore, if the buildings directly join the existing CT market, they will have insufficient motivation to participate in the trading due to the low trading price and high EEI cost, which makes it difficult to form a sufficient scale of building trading units the market needs. In fact, Japan set the trading price at about 770 CNY/tCO_2 at the beginning of BCT in 2010 over 10 times of that in current China, although the price has now sharply declined to 34 CNY/ tCO_2 even lower than that of China, as is shown in Fig. 6.

In recent years, due to the pressure of carbon neutrality target and the high proportion of carbon emissions from the building sector (could be up to 60% ~ 75%), more and more countries and cities are planning to bring the building sector into the CT market. New York enacted Local Law 97 in November 2019, and required that 50,000 of the city's large buildings should participate in CT to help New York City reach the goal of a 40 percent reduction in greenhouse gas emissions from buildings by the year 2030, while the annual carbon-emission limits would start in 2024 and tighten significantly through to 2050, with sizable fines for noncompliance (NYC Sustainable Buildings 2022). Von der Leyen confirmed in April, 2021 that the EU CT market would apply its emissions trading

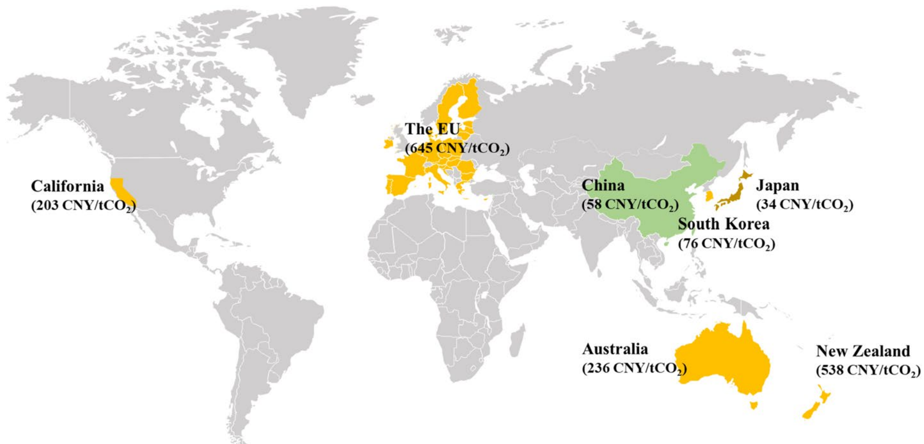
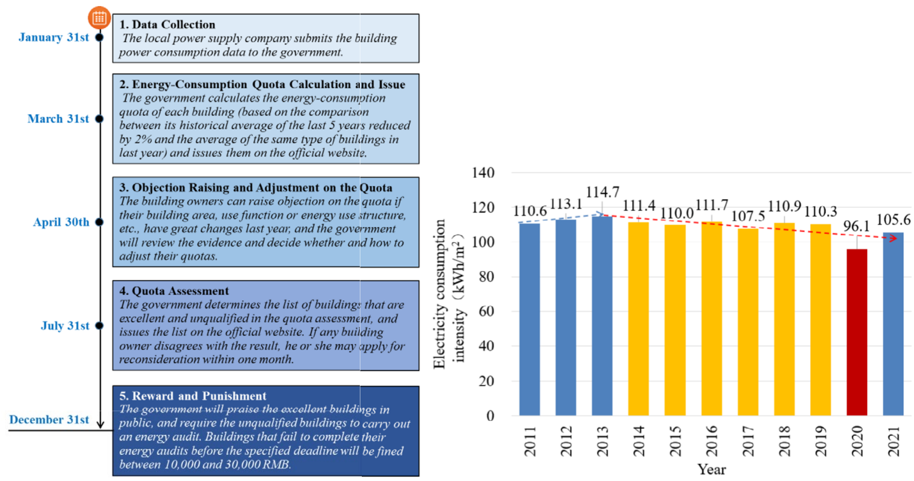


Fig. 6 The carbon trading price in typical markets on December 24, 2022 (CarbonCredits.com 2022) (Bureau of Environment. Tokyo Cap and Trade 2022) (where 1 CNY can be exchanged for 0.1348 €, 0.1431$, and 19 yen on December 24, 2022)

scheme to buildings and transport, as part of a package of policies designed to make every economic sector greener (Euractiv 2022). The German government decided to put a price on greenhouse gas emission in the building and transport sectors from 2021 as a key instrument to help reach its climate targets, and the fixed price was set at 25 € in 2021 and 30 € in 2022 (EURACTIV.com with Reuters 2022). The cities of Xiongan New Area (Management Committee of the Xiongan New Area 2022), Wuhan (People's Government of Wuhan Municipal 2022) and Shanghai (Commission and of Housing and Urban–Rural Development 2022) in China also proposed in 2021 in their local planning to explore the establishment of a carbon trading mechanism in the building industry in recent years, as one of the key policies to support the national and local "double carbon" goal.

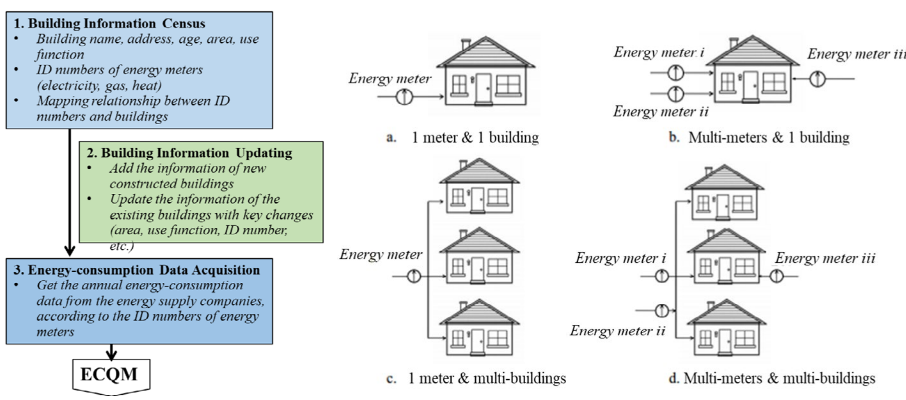
Energy consumption quota management

Energy consumption quota management (ECQM) is a unique EEI policy tool used in China. First of all, a local energy consumption quota (ECQ) standard should be formulated, which defines the "red line" (up limit) for the annual EUI of different types of buildings based on the statistical results of the buildings' measured energy consumption in the region. Since 2013, nearly 50% of China's provinces and cities have issued local ECQ standards. However, most of the local governments have only taken the standards as a reference basis for a series of policies related to the building energy-use management, only the Beijing government uses it as a tool to carry out direct management, evaluation, reward and punishment on the annual energy-use of public buildings larger than 3,000 m^2 every year (Commission and of Housing and Urban–Rural Development 2014) (Commission and of Housing and Urban–Rural Development 2020). Figure 7a illustrates the main processes of ECQM of the public buildings in Beijing. Since its launch in 2013, the ECQM of public buildings in Beijing has covered 14,499 buildings (196 million m^2, accounting for about 50% of the city). A total of 7 annual assessments have been carried out, successfully curbing the rapid growth trend of electricity consumption intensity of public buildings, as is shown in Fig. 8b, and saving electricity



(a) Process of ECQM in Beijing (b) Electricity consumption intensity year by year

Fig. 7 ECQM of public buildings carried out in Beijing, China. **a** Process of ECQM in Beijing **b** Electricity consumption intensity year by year



(a) Data acquisition process (b) Mapping relationship between energy meter and building

Fig. 8 Data collection in the ECQM in Beijing. **a** Data acquisition process **b** Mapping relationship between energy meter and building

by 4.01 billion kWh, equivalent to a reduction of 2.48 million tons of carbon emissions (Conservation et al. 2021).

Large-scale collection of building energy consumption data is the biggest challenge and difficulty in carrying out ECQM, which is the main reason that hinders other provinces and cities to carry out this work. Interestingly, Beijing has insisted on cooperating with the power supply companies to obtain the public buildings' power consumption data at the beginning of ECQM, making full use of the existing data collection resources of the energy supply companies. Under the pressure of the "double carbon" goal, "Action Plan for Carbon Peak by 2030" issued by the State Council of China (Council and of China 2030), "Implementation Plan for The Carbon Peak in Urban and Rural Construction" issued by the MHUD and the NDRC (Ministry of Housing and Urban–Rural Development (MHUD) National Development and Reform Commission (NDRC) 2022), and the related action plan in Shanghai (People's Government of Shanghai Municipal

2022), Jiangxi (People's Government of Jiangxi Province 2022), etc., all have clearly proposed to carry out or gradually implement ECQM in public buildings, where the historical practice of Beijing could provide a sample reference for the cites and provinces.

Analysis of problems and related-reasons of EEI policy tools in China

This section summarizes the main problems or challenges encountered by both the managers and the managed throughout the process from the design to implementation of the EEI policy tools and discusses the related reasons found in the field investigation and interviews.

Large-scale data collection and disclosure

Measured energy-consumption data is the basis for the development and implementation of EEI policy tools for public buildings, such as the development of EUI baseline and quotas, but it is very difficult to collect building energy consumption data on a large scale of city level, with high accuracy and fine granularity.

In the energy benchmarking mechanism of the US and EU, the building energy consumption data is uploaded by the building owners themselves. However, the owners, especially those with relatively high energy consumption, are worried that the data submission, disclosure and comparison process will expose their business privacy, or affect the reputation of the enterprise and attract penalties from the government, and so have negative attitude in the cooperation with the government. For example, only 176 buildings (9.5%) of more than 1,800 large public buildings in San Francisco submitted their annual energy-consumption data during the benchmarking period from 2010 to 2014, and even false low energy consumption data were submitted found in Seattle (Trencher et al. 2016). The cities have tried serval methods to alleviate the difficulty and improve the accuracy of data collection, such as developing easy-use and beneficial data processing tools (e.g. "ENERGY STAR PortfolioManager" in the US), cooperating with universities to develop separate tools for data cleaning, common errors or outlier checks, hiring professionals to check the data and feedback the error information to the owners, and even considering penalties for inaccurate data submissions (Takagi et al. 2015).

Meanwhile, public disclosure of the energy-consumption data is considered as a potential driving force to improve the market competitiveness of building assets, and thus could be an incentive for the building owners to do EEI. However, only a few cities have achieved public disclosure of the collected individual building energy-consumption data on the city website, such as New York, while most of them have suffered from opposition from the building owners, such as Seattle in the US and Japan (Takagi et al. 2015). The programme of "Medium and Small-sized Enterprises Carbon Reduction Report" carried out in Tokyo, Japan found that the choice to publicly disclose the carbon emissions rather than the original energy consumption could make the plan more attractive to enterprises (Bureau of Environment. Tokyo Cap and Trade. 2022). More and more cities are trying to make the disclosure of building energy consumption data mandatory through legislation, and require priority disclosure on municipal facilities and buildings (Takagi et al. 2015).

The way of building energy-consumption data acquisition in China is much different from the cities talked above, but similar problems also exist. During 2007 and 2013, the governments of 18 piloted provinces and cities in China, including Beijing, Shanghai, Shenzhen and Jiangsu, have successively invested billions of CNY to install real-time monitoring devices of energy-consumption data for large public buildings (over 20,000 m^2) as well as build the city or province level data monitoring platforms (Ministry of Housing and Urban–Rural Development Ministry of Finance of the People's Republic of China 2007), so as to grasp the energy consumption dynamics of urban public buildings. The total and sub-item energy consumption of over 11,000 buildings (240 million m^2) were reported to be monitored and connected to local city or province level platforms. However, surveys found that most of these data monitoring systems were abandoned or stopped updating within 2 to 3 years after completion (Conservation et al. 2021). One reason is the lack of continuous government financial investment to keep the systems continuously running due to excessive fault maintenance workload, and the other one is that the building owners cut off the power supply or network of the monitoring sensors for fear that the government would find problems and bring punishment to them. At present, the systems of only a few cities, such as Shanghai and Shenzhen, are still in operation, but the coverage of the building samples are small, where Shanghai covers 2017 buildings, accounting for only 22% of the city's total area of public buildings, while the two values in Shenzhen are 659 and 18%. Meanwhile, the local governments must also spend millions of yuan every year to maintain the systems.

As mentioned above, Beijing has established a power consumption database of 14,499 public buildings (50% of the total public building area in Beijing) in its ECQM programme by cooperating with the power supply companies. As the energy supply companies often only grasp the information about energy users and corresponding energy meter ID number rather than that related to buildings, so the basic information of public buildings should be manually collected first, including the building name, address, age, area, use function, and the ID number of energy meters (electricity, gas, heat) as well as the mapping relationship between the ID numbers and buildings, as is shown in Fig. 8a. In 2013, more than 7,000 personnel from the construction departments in 17 districts and counties, more than 300 sub-district offices (or township governments) and the communities under their jurisdiction in Beijing, invested in the building information census of a total of 18,870 public buildings (Conservation et al. 2021). Among them, the information of mapping relationship between the energy meters and buildings is the key to linking the energy meters with buildings, and the most time-consuming as 4 types of mapping relationship were found, namely, "1 m & 1 building", "Multi-meters & 1 building", "1 m & multi-buildings", and "Multi-meters & multi-buildings" (shown in Fig. 8b). Since the data from energy meters is used for energy fee settlement by the energy-supply companies, its accuracy is beyond doubt, which helps eliminate saves the workload of the government on data accuracy check. However, as Beijing and many other cities in northern China have not yet metered the heating energy consumption of each individual public building, and the proportion of gas energy consumption in a building is relatively small, Beijing has been carrying out quota management only on the electricity consumption rather than the total energy consumption (sum of electricity, gas and heat consumption). According to the survey of small samples, the electricity consumption only accounts for 60 ~ 75% (large buildings) and 45% ~ 55% (small and medium-sized buildings) of the buildings' total energy consumption (Zhou et al. 2022b). Therefore, Beijing has been seeking to expand the quota management to full energy consumption in recent years, where the heat and gas consumption will be also derived from the energy supply companies. However, how to add these two meters into the already complex enough mapping relationship between electricity meter and building will be the biggest challenge for Beijing government.

Although as early as 2008, China has written the requirements for the public disclosure of building energy consumption data into the national law "Regulations on Energy Saving for Civil Buildings" (The State Council of the People's Republic of China 2022), it has not yet been successfully implemented in any cities due to the opposition from the market, lack of specific publicity standards, and the difficulty to guarantee the accuracy of data.

Evaluation method of building energy efficiency

The actual measured energy consumption is the most key index to test whether a building is really energy saving or energy efficient. However, the design energy-saving rate, compared to a reference benchmark building and calculated in the building design stage, is right the key evaluation index in current evaluation systems in China.

As mentioned above, the countries such as the EU and US, use different color bars to mark the actual energy consumption (or efficient) level of the buildings, which is intuitive and clear to tell whether a building is energy-saving (or energy efficient). Due to the lack of large-scale building measured energy consumption database with high accuracy, it has been difficult for China to formulate the energy-consumption baselines and classification standards for various types of public buildings in different climate zones, provinces and cities. Thus, the energy-saving related assessment systems already established in China (shown in Table 1), such as the certification for green building (since 2006) and nearly zero energy building (since 2019), and energy efficiency evaluation and grading (since 2008), all did not specify the measured energy-consumption limits for buildings with different certification grades, but used the calculated design energy-saving rate as the main evaluation index. This mechanism has led to the following two widespread phenomena in China.

One is that the real estate developers become "Valuing Design, Neglecting Operation" (pay attention to the design quality, but do not care about the operation quality). As long as the buildings pass the energy-conservation checks and obtain any certification label (e.g. Green Building Design Label) upon completion, the developers could use the label as a publicity point to improve market competitiveness for higher selling or rent price, and so are not active in EEI during the building operation. For example, none of the 377 public buildings that have derived "EEEG" certification in China by far updated their labels with measured energy consumption data, and the green buildings certified in operation stage only account for 6.35% of more than 24,000 buildings that have received green building labels in China (Dai et al. 2023).

The other one is that the government decides the list of buildings t in urgent need of energy-efficient renovation right based on the completion years of the buildings which are actually corresponding to the versions of building design standards and design energy-saving rates, rather than the actual energy consumption. For example, older buildings are always required to be renovated first. In fact, a large number of measured data showed that, high design energy-saving rate did not necessarily lead to low actual measured energy consumption due to the influence of the actual construction quality, operation ability and use habits (Wu et al. 2020). Similarly, it is not necessary that the older a building is, the more energy it must consume, as is shown in Fig. 9, where the average electricity consumption intensity (red line in the boxplot) of those buildings completed before 2000 are lower than those built after 2000 in most types of buildings.

London has required that the energy efficiency of all the public buildings in the area should reach Grade C before 2027 (Grade C represents a good performance in energy-use), which means that all the buildings with a DEC label below Grade C (namely, D, E, F and G) should carry out energy-saving retrofitting to climb to Grade C. In this way, both the target group of buildings that should carry out retrofitting and the energy-efficiency target that should be achieved after retrofitting are very clear, which is worth learning for China. Although China issued the national "Standard for energy consumption of building (GB/T 51161–2016)" in 2016, and various provinces and cities have also issued similar local energy consumption (quota) standards, hardly any of these standards have been directly used as in the current evaluation systems.

Application and feedback of the data

At present, the city governments in China spend a lot of manpower and financial resources to collect, check, evaluation, and use the building measured energy-consumption data in several tasks such as different types of building performance evaluation (e.g. green building certification), ECQM, energy-use related statistics and planning, but most of the data will be shelved, and finally form series of "data grave". Meanwhile, the building owners, who provide the data, receive very limited feedback and incentives after getting the certification or financial reward (e.g. from energy-saving retrofitting) from the government. If they continue to provide data to the government, often they could not get any economic benefits or technical supports, but have to bear a certain pressure and burden that may be punished by the government (e.g. punished in the ECQM in

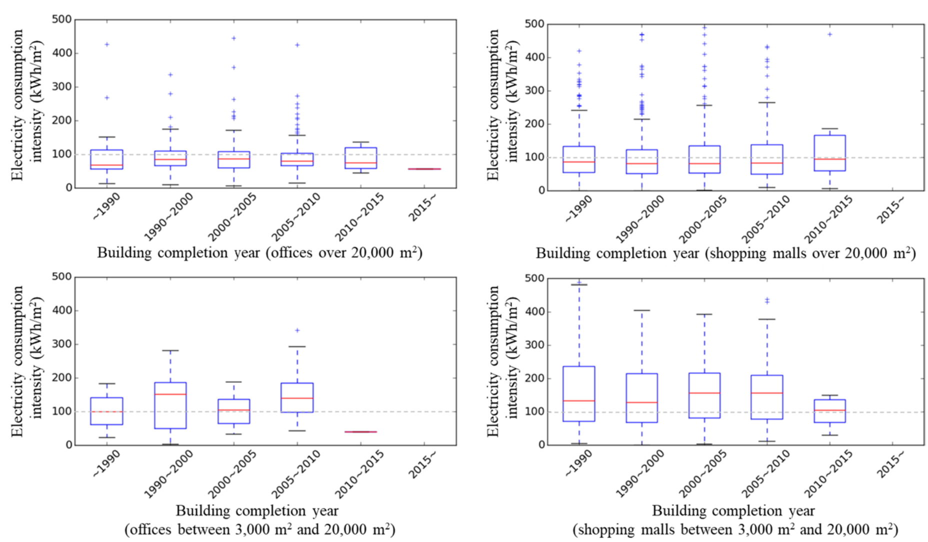


Fig. 9 Electricity consumption intensity of buildings with different types and completion years in Beijing

Beijing if their energy-consumption exceed the quotas), which leads to the lack of incentive for the building owners to continuously participate in the energy-consumption data submission and EEI policies proposed by the government, as is shown in Fig. 10.

In fact, in the field investigation and interviews in the 29 typical green and 41 ordinary public buildings in Beijing, the team found that most of the building owners and operation teams have certain demands for the city's building energy consumption data (database), including finding out excellent buildings with high energy efficiency to learn design and operational experience, evaluating the energy-saving effect of various measures based on the measured data from other excellent cases of energy-saving retrofitting so as to help themselves to develop a reasonable retrofitting plan, finding the market recognition and competitive advantage publicity points through the comparison with other similar buildings, etc.

The government in Shanghai and Shenzhen released a data analysis report every year, and the data right came from the city-level building energy consumption monitoring platform, which is very rare cases of building energy-consumption data publicity in China. Although, the main purpose of these reports was to highlight the government's achievements in building energy-conservation management, and the information released in the reports was often the statistical average results of all buildings, lack of the energy-consumption details of individual samples, which is difficult to give the building owners a very specific scheme reference.

The US government right uses the energy benchmarking mechanism and the energy consumption data analysis tool ("ENERGY STAR PortfolioManager"), which could give very direct and rich feedback to the data submitters, and so can attract more and more building owners to continuously submit their data and participate in the EEI work. However, the government departments in the building sector in China are still very cautious about data disclosure, worried about exposing the privacy of the vast public buildings and causing complaints, and have not yet found appropriate mechanisms to do data disclosure, sharing and service.

Association mechanism between building energy-related stakeholders

In the field investigations, the team found two typical types of association mechanism between building energy-related stakeholders hindered the buildings from improving

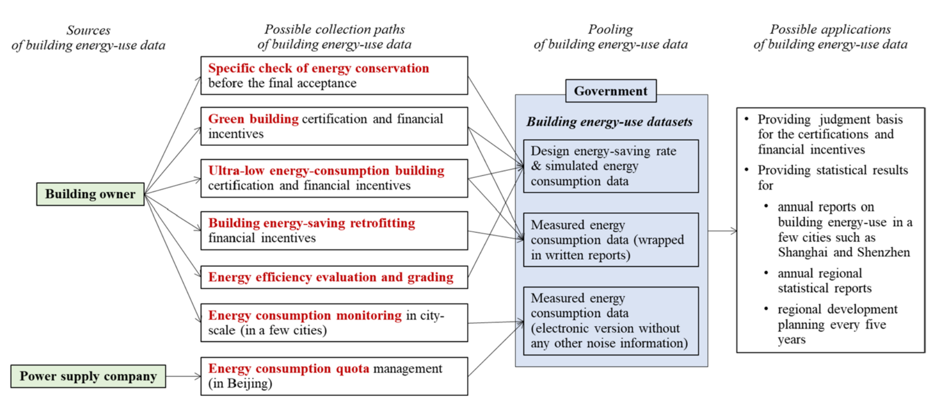


Fig. 10 Data flow framework (one-way without feedback)

their energy efficiency. One is that between the public institutions and government financial departments. In China, the financial departments pay all the energy cost for the public institutions as much as they actually used, and the public institutions can only apply to the financial departments for the replacement of energy-use devices at the date of retirement even if the devices' energy efficiency is measured actually very low. Meanwhile, all the economic benefits obtained from the public institutions' efforts on EEI will be taken back by the financial departments, and so could not be used to encourage the operation team or share with the energy-saving service providers. As a result, the directors of public institutions are commonly much less motivated to make efforts on EEI than the owners of commercial buildings. It is reported that more than 50% of the buildings which have exceeded the annual electricity-consumption quotas were from public institutions in the past years (Conservation et al. 2021).

The other is that between the tenants and building owners. The building owners attract more high-quality tenants to use the building by providing high-quality services especially in the 3 years since the COVID-19 outbreak, so all the demands from the tenants will be granted, including free choice of energy systems, use of more energy and high standards of indoor environmental quality. For example, the tenants from one investigated building were the branches of international financial institutions in China, and they required that within 24 h every day the room temperature should be kept at 24℃, the indoor $PM_{2.5}$ concentration below 0.015 mg/m^3, and the fresh air supply not lower than 50 cubic meters per hour per person, which were all much higher than the requirements of local standards (not lower than 26 ℃ in summer and not higher than 20 ℃ in winter, 0.075 mg/m^3, and 30 cubic meters per hour per person, respectively within 8 working hours). As a result, the EUI of this building could be 2 times of the average value of the same type buildings in Beijing. To make matters worse, most of the buildings included the tenants' energy costs in the property management fee which was charged by the rented area, so the tenants preferred to consume energy without any restraint in a limited area, and were unwilling to share the cost of energy-saving retrofitting with the building owners. As a result, even if the building owners really wanted to improve the energy efficiency, they can only carry out some no-cost or low-cost retrofitting measures targeted just at the public areas, energy saving effect of which was often very limited.

The concept of architectural design and mass consumption

In order to pursue a beautiful appearance, more and more architects like to design buildings into glass curtain wall structures, and this type of buildings can be seen everywhere on the streets of Beijing. As the thermal performance of the glass curtain wall is poor compared with that of the general building, the indoor air temperature of the south-facing room which receives excessive solar radiation heat is too high in summer, while that of the north-facing room which receives no solar radiation heat is too low in winter, and the temperature difference between the south-facing and north-facing rooms could reach 5 to 10 degree at the same time, as is shown in Fig. 11. As a result, the buildings need to do its best to cool the south-facing rooms in summer and heat the north-facing rooms in winter. Meanwhile, the number and size of open vents available on the surface of glass curtain wall buildings are very small, the fresh air system needs to be opened larger and longer than the general buildings. Moreover,

Fig. 11 Some of the problems found in glass curtain wall buildings

the curtains in most rooms are closed against the glare when the sun is strong, leading to longer artificial illumination. All of the problems mentioned above will cause the glass-curtain wall buildings to consume more energy than general buildings, and once the buildings are completed, both the energy-saving paths and effect of management or low-cost retrofitting measures are very limited, reported by the investigated building owners.

It is difficult to say exactly when it started that the public generally believes that large central air conditioning systems are more high-end, magnificent and classy than the small distributed ones. Most of the investigated buildings were designed with a whole central air conditioning system without any further subdivision in space or distributed supplement, even though there were spaces for different functions in the building. As a result, 90% of the buildings were found having to run the entire central system to provide a very small portion of the building in many scenarios, leading to a huge waste of energy. For example, in commercial complex buildings, the office part of the same building was generally off work around 5 or 6 p. m., while the commercial part (usually covers only one or two floors of the entire high-rise building) was often running until 9 or 10 p. m, and in single office buildings, there was always a small amount of offices working overtime at night. In such cases, a distributed air conditioning system as a supplement, such as split or VRV (Variable Refrigerant Volume) air conditioning, might well solve the above problem of energy waste. However, in the concern that distributed air conditioners is not high-end enough or its outdoor unit affects the building appearance, the building did not consider the spatial location for distributed air conditioners at the beginning of the design.

In summary, due to the inherent defects in energy efficiency caused by the above architectural design and consumption concept, it is difficult for many buildings to greatly improve their energy efficiency even with their best efforts.

Design and discussion of possible coping strategies

Establishing the mechanism of large-scale data collection with appropriate cost

The experiences of Beijing, Shanghai, and Shenzhen should be promoted across the country of China to help other cities establish a city-scale energy consumption data collection mechanism for public buildings with appropriate cost. Firstly, the requirements for public buildings and energy supply enterprises to provide building measured energy consumption data to the government departments should be clarified in the local legislative documents, so as to smooth the data collection paths. Secondly, referring to the experience of Beijing, the local governments need to carry out a census of the ID numbers of the meters of electricity, heat, and gas over the large and medium-sized public buildings in the area, as well as the mapping relationship between buildings and meters, and then get the corresponding energy consumption data from energy supply companies, so as to build a city-scale data base. Thirdly, all the new constructed, extended, renovated, or retrofitted public buildings should be required to submit the ID numbers of the energy meters and their mapping relationship with the buildings (referring to Beijing), or install energy metering devices which have connected to the city level data monitoring platform (referring to the Shanghai and Shenzhen), so as to form a continuous supplement and update mechanism for the building energy-consumption data.

Constructing a building energy-consumption grading and management system based on the actual measured energy-consumption data

The government and practitioners shall gradually turn the key principles of developing building energy-saving design standards and evaluation systems from measure-oriented framework which controls the calculated and relative energy-saving rate, to effect-oriented one that controls the absolute total design or measured energy consumption. And then, the government of every province or city shall compile local standards of energy consumption for building operation stage, which may clarify the energy consumption and carbon emission intensity limits and grading rules for buildings, including different types of ordinary public buildings, different star rating and types of green buildings, ultra-low or net-zero energy consumption buildings, and low or zero carbon emission buildings, etc.. Then, different management countermeasures can be designed aiming at buildings with different energy consumption levels (grades). For example, the government can focus on the both ends, namely, buildings with the highest and lowest levels, where the former will be mandatory for energy audits, energy-saving retrofitting, or suffer from punitive increases in electricity prices, and the latter will be rewarded with a notification of praise, financial subsidies or reduced electricity prices. Moreover, with the help of grading rules, cities can also establish a large-scale benchmarking and data disclosure system for building operation energy consumption based on GIS (Geographic Information System) technology.

Figure 12 illustrates the energy-consumption grading and management system designed in Beijing, where the building energy-consumption levels will be divided

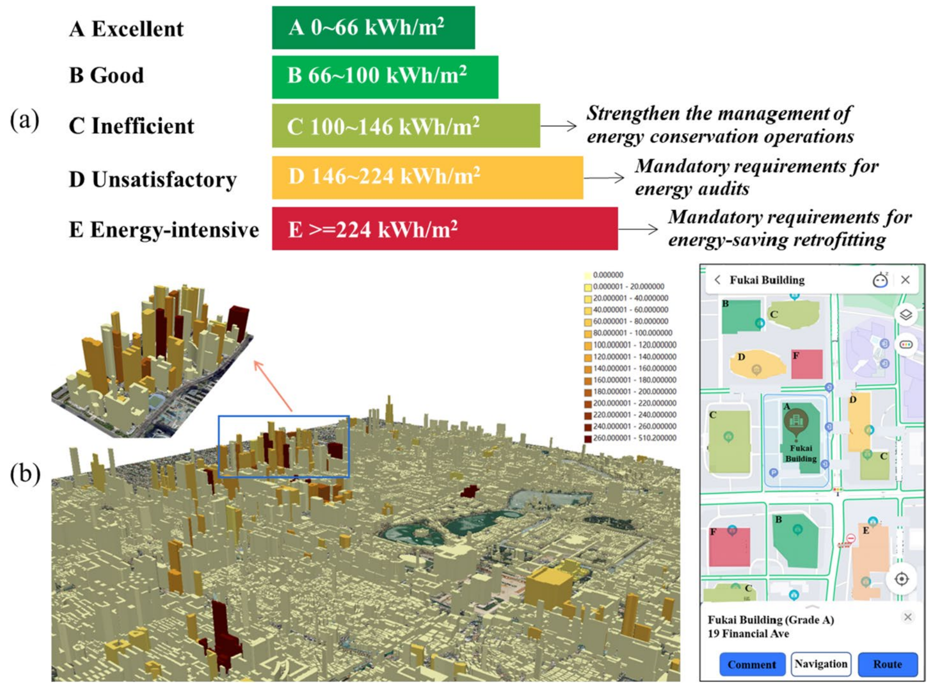


Fig. 12 Energy-consumption grading and management system designed in Beijing, **a** energy-consumption grading and management rules (taking the office building samples as an example), **b** energy benchmarking and data disclosure on the city map through the web and mobile apps

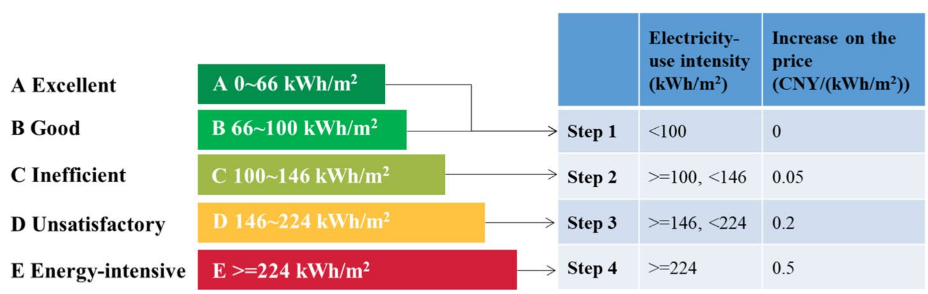


Fig. 13 A differential electricity pricing mechanism designed on the base of energy grading (taking the office building samples as an example)

into 5 grades from E (Energy-intensive) to A (Excellent), and the node value that distinguishes Grade B and C represents the average energy-consumption level of this type of building (100 kWh/m^2 in Fig. 13). The buildings classified into Grade C will be required to strengthen the management of energy conservation operations, and those into Grade D should carry out energy audits, and Grade E should carry out energy-saving retrofitting. Meanwhile, a mechanism for energy benchmarking and data disclosure through the city map is also designed, using both the web and mobile map apps. With the help of mobile maps, the government can also collect and visualize the subjective evaluation and feedback information on building energy-use performance from the local consumers, so as to strengthen the general public's awareness of building energy saving.

Giving full play to the link role of data between the government and building owners to establish a closed loop of EEI policy

The government should make efforts to establish a benign closed loop from data collection, governments' management and service, to the building owners' EEI and benefit harvest, so as to push the EEI policies to continue to work. Firstly, take the results of energy-consumption grading and benchmarking as an essential prerequisite for a series of EEI policy tools, including the certifications and financial rewards of green buildings, ultra-low energy consumption buildings and energy-saving retrofitting buildings, ECQM, catalogue construction of high carbon-emission buildings, housing rental and sale price setting, and financial support for low-carbon building technologies, etc.. Secondly, lead the establishment of a regular expert inspection mechanism, so as to increase the service supply on energy-saving and carbon-emission reduction technologies and data in city scale. The field investigations and face-to-face interviews in 70 buildings carried out in this study did receive good feedback from the building owners, acclaimed as a kind of "warm" management. Thirdly, widely invite the building owners, operation and maintenance teams, energy saving service providers and other stakeholders to participate in the design of EEI policies, tools and the technical guides on energy-saving operation. Fourthly, the public institutions should take the lead in pilot EEI policy tools and adopting stricter and more refined energy-saving management measures.

Exploring a new model of carbon-emission trading independent of the existing trading market for public buildings

Create a building carbon trading model that is independent from the existing trading market, and promote the mechanism of "year-by-year energy quota management + 5-year carbon quota trading" in pilot cities such Beijing, Shanghai and Shenzhen. On the one hand, promote the tool of ECQM and Beijing's experience in every province or city in China, where the buildings' energy use will be assessed and the building owners rewarded or punished year by year, so as to continuously urge them to continuously improve energy efficiency. On the other hand, raise the carbon price to 5 to 10 times of the current one, and carry out one time of building carbon quota trading every 5 years, where large public buildings are forced to participate, and small and medium-sized buildings can voluntarily participate through the aggregation of integrators. Through the way of time and spatial accumulation, the problem of small and scattered carbon-emission of each single building could be alleviated. According to the statistics, the total carbon emissions of buildings included in the Beijing ECQM system can reach 30% of the total carbon emissions of the building sector in Beijing, so if all these buildings participate in carbon trading and achieve an average of 15% energy-saving within 5 years, it can contribute a carbon emission reduction by 4.5%.

Establishing a differential electricity pricing mechanism and improving the flexibility of electricity use in public buildings

Adjustment of electricity price is considered to be an important approach to control building energy consumption. The electricity price at the peak hours (8–11 a.m. and 16–21 p.m. in Beijing) in some cities in China has reached more than 5 times of the one at the valley hours (22–6 p.m.). Therefore, it is necessary to develop a new differential price mechanism to mete out rewards and punishments to low and high energy consumption buildings as soon as possible, so as to give full play to the role of the market in energy allocation. The team has designed two differential electricity pricing schemes in Beijing, where One of the schemes is a type of punitive pricing (Scheme 1), and the other one multi-step pricing (Scheme 2). Scheme 1 was designed on the base of the policy tool of ECQM, where the electricity price would be increased by 0.2 CNY/kWh for buildings who had consumed electricity over 20% but not more than 100% of the quota, and by 0.5 CNY/ kWh for those who had consumed electricity over 100% of the quota. Scheme 2 was designed based on the energy grading system, where the electricity was priced with 4 steps which were partitioned by the electricity-use intensity upper limits of Grade B, C and D, relatively, as is shown in Fig. 13, and the increase on the price for Step 1 to 4 were 0, 0.05, 0.2 and 0.5 CNY/(kWh/m^2), relatively. If all the buildings in the Beijing ECQM system are taken as the calculation samples, the costs of the two schemes due to the price increase could reach 2.83 and 1.38 billion CNY, relatively, which is about 25% and 10% of the total electricity cost before the price increase. As the punishment intensity of Scheme 2 is more moderate than that of Scheme 1, Scheme 2 is more recommended to the government. Moreover, if 10% of the increased cost in Scheme 2 is used to reward buildings within Grade A also through electricity pricing, the price can be reduced by 0.16 CNY/(kWh/m^2).

Meanwhile, priority in southern cities should be given to guiding and promoting the technologies that could improve the flexibility of electricity use and the capacity of demand side response in public buildings, including ice or water storage, electric vehicle storage, and building energy metering, etc., so as to make better use of the difference between peak and valley electricity prices and absorb more unstable renewable energy.

Innovating financial approaches to support buildings in their efforts to carry out EEI

The government should guide and work with financial institutions to develop diversified green financial products to support buildings in their efforts to carry out EEI, and simplify the application process and lower the entry threshold of these supports as much as possible, including: 1) providing green credit and green insurance for participants in the whole chain of newly built, renovated and modified high-performance public buildings from development, operation and maintenance and building materials production, as well as investors in low-carbon innovative building technologies such as site solar photovoltaic, renewable energy utilization, and energy performance contracting, etc.; 2) promoting green leasing in China to clarify the responsibilities and obligations of the owners and tenants in the energy-saving operation and retrofitting of the buildings (Green leasing has been widely used in the US but not yet been introduced in the Chinese building sector, and proved to achieve up to 22% energy-saving (Leaders et al. 2023)); 3) providing preferential policies such as low-interest loans and tax relief for the construction, purchase and rental of high-performance buildings including green, ultra-low energy, low-carbon, energy-saving retrofitted and Grade A buildings, etc.; 4) giving financial subsidies to the buildings who carry out energy audit or retro-commissioning, especially those built before the year of 2000.

Conclusions

Through review and comparison of domestic and foreign literature, and field investigations and interviews with experts, building owners and operation teams in 70 public buildings in Beijing, the study comprehensively analyzed the development status, problems and challenges of EEI policy tools in China, and provided possible coping strategies for the future policy modification.

The following conclusions are drawn:

1) The global building EEI policy tools could be divided into 3 categories and 11 subcategories, among which energy grading and labeling, energy benchmarking, carbon-emission trading and energy-consumption quota management were all designed based on buildings' actual operational energy consumption data, and first three had been widely used in the US, EU and some developed Asian countries, while the last one was unique to China.
2) The difficulty in large-scale data collection and disclosure of building energy-consumption, lack of scientific evaluation methods about building actual energy-use level, limited application of the big data and hardly any feedback to the building owners, undesirable association mechanism between building energy-related stakeholders, and pursuit of large glass curtain wall and central air conditioning which were both high energy-consuming practices in architectural design, were the main 5 obstacles for achieving the long-term effectiveness of the EEI policy tools.

The following possible coping strategies are drawn:

1) The experiences of Beijing, Shanghai, and Shenzhen should be promoted across the country of China to help other cities establish a city-scale energy consumption data collection mechanism for public buildings with appropriate cost.
2) The government should compile local standards of energy consumption for building operation stage, and gradually construct a building energy-consumption grading and management system based on the actual measured energy-consumption data.
3) Efforts should be made to establish a benign closed loop from data collection, governments' management and service, to the building owners' EEI and benefit harvest, so as to push the EEI policies to continue to work.
4) A building carbon trading model should be designed independent from the existing trading market, and the mechanism of "year-by-year energy quota management + 5-year carbon quota trading" could be promoted in pilot cities such Beijing, Shanghai and Shenzhen.
5) A differential electricity pricing mechanism might be developed to control building energy consumption, and the technologies that could improve the flexibility of electricity use in public buildings should also be promoted so as to make better use of the pricing mechanism.
6) The government should guide and work with financial institutions to develop diversified green financial products to support buildings in their efforts to carry out EEI, and simplify the application process and lower the entry threshold of these supports as much as possible.

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Authors' contributions
Hao Zhou: Conceptualization, Methodology, On-site investigation, Data analysis and visualization, Writing—original draft, Writing—review & editing. Xin Tian: On-site investigation, Policy analysis. Yang Zhao: Data curation, Investigation, Validation, Visualization. Chenchen Chang: Conceptualization, Data curation, Formal analysis, Investigation. Borong Lin: Conceptualization, Funding acquisition, Methodology, Supervision, Writing—review & editing.

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Availability of data and materials
The data of this paper came from the Beijing Municipal Commission of Housing and Urban–Rural Development and the extensive field research work conducted by the authors. As the data involves a lot of energy use and commercial information of public buildings in Beijing, the application scope of the detailed data is strictly limited. Data can only be available from the authors upon reasonable request and with the permission of the Beijing Municipal Commission of Housing and Urban–Rural Development.

Declarations

Ethics approval and consent to participate
Ethics approval was not required for this research.

Competing interests
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.

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