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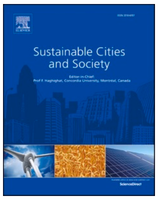

Subsidy allocation for residential building energy retrofit: A perspective of families' incomes

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ABSTRACT

High household end-user services demand of high-income families results in higher energy consumption compared with low-income families, indicating high-income families may save more energy from similar building energy retrofitting (BER) strategies. Therefore, current BER subsidy policies, which consider technique indicators and ignore families' income, will make high-income families' recovery costs faster, and can't maximize the incentive for residents' BER awareness. To formulate a equitable and efficient subsidy policies considering families' income, this study selected Chongqing as the study case and employed propensity scores matching method to evaluate BER's actual energy savings performance for families with different incomes. Meanwhile, the BER subsidies are reallocated based on the dynamic cost payback period. The results indicated that, following BER, the energy savings of high-income families (7.36 kWh/m^2) were higher than the mid- (3.96 kWh/m^2) and low-income (3.25 kWh/m^2) families. Notably, under current subsidy policies, the cost payback period of low-income families is nearly 2.55 and 3.14 times of the mid-income (6.61 years) and high-income (5.37 years) groups, respectively. This study suggests a subsidy of 32.57 yuan/m^2, 20.27 yuan/m^2, and 15.38 yuan/m^2 for low-income, mid-income, and high-income families, respectively. These results provide novel insights into the actual energy-saving performance of residential buildings and help policymakers to formulate fair subsidy policies.

1. Introduction

As one of China's three major final energy consumption sectors, energy savings from the building sector play an important role in realizing China's goals to achieve a carbon peak by 2030 and carbon neutrality by 2060 (Wang, 2022; Xiang, 2023). Building energy retrofitting (BER) can break the carbon lock-in effect, and is one of the most effective building energy-saving strategies (Chen et al., 2023a; You et al., 2023). Up to 2050, it can potentially reduce the energy consumption of the building sector by more than 20 % in China (Guo et al., 2021).

Promoting BER faces severe challenges since high implementation cost (Choi et al., 2023; Jiang et al., 2022; Kim & Lim, 2021). Some scholars have suggested that subsidies are imperative to promote BER (Jiang et al., 2022; Liu et al., 2023). Chinese government has published a series of subsidies and finance policies at both national and provincial levels. For example, the Ministry of Housing and Urban-Rural Development of China provides a subsidy of 15 yuan/m^2, 20 yuan/m^2, and 25 yuan/m^2 for the east, middle and west areas, respectively, for China's hot summer and cold winter areas. These subsidies are used to conduct BER and improve the performance of external doors and windows, exterior shading systems, and exterior insulation systems (MOHURD, 2012b). In addition, Shanghai provides a subsidy of 50 yuan/m^2 for the energy retrofit of existing residential buildings (HUCAS, 2020).

Abbreviation: BEES, Building energy efficiency standard; BER, Building energy retrofit; CABEE, China association of building energy efficiency; HSCW, hot summer and cold winter area; PSM, Propensity matching scoring; ASHRAE, American society of heating, refrigeration, and air-conditioning engineers; MOHURD, ministry of housing and urban-rural development; HDD, heating degree days; ATT, average treatment effect on the treatment; H&C, heating and cooling; DCPP, dynamic cost payback period; DE, department of energy of the USA; DBEIS, department for business, energy & industrial strategy of UK..

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However, the calculation regulations of such subsidies are based on technique-related indicators (e.g., adopted equipment, and floor area) while ignoring the difference in families' economic condition, especially for income. Existing studies have shown an allocative effect of energy efficiency policies (i.e., high-income families may account for larger share of limited BER foundation) (Egner et al., 2021; Lekavičius et al., 2020; Rivers & Shiell, 2016). Therefore, these calculation regulations may harm the efficiency of subsidy policies since high-income families may benefit more from energy savings.

High income leads to a higher end-user services demand, which needs to be met by more household equipment and a longer utilization period, thereby increasing absolute household energy consumption (Chen et al., 2023b; Huo et al., 2021a; Santin, 2011). Previous studies have confirmed this relationship. Huo et al. (2021a) indicated that increased income might lead to a rise in heating equipment usage and heating period, significantly promoting building energy consumption. Jones and Lomas (2015) indicated that high-income families were more likely to be high electrical-energy users, owing to the increase in the use of electrical appliances and the ability to afford higher electricity bills. However, due to the similar energy savings rate derived from similar building energy retrofit strategies, high-income families may obtain more energy savings than low-income families. However, they pay the same cost and enjoy the same subsidy. In other words, the high-income family may enjoy more economic benefits from energy savings measures and spend a shorter period recycling their BER cost. Therefore, subsidies or financial policies that only consider techniques indicators are unfair, and may hinder wider promotion of BER.

To develop equitable BER subsidies, in this study, two issues be addressed:

- What is the actual energy savings performance of BER for families with different incomes?
- How to fairly reallocate building energy retrofit subsidies while considering families' incomes?

To solve the above research questions: this study aimed to establish a framework for establishing a subsidy system considering families' income, which can be replicated worldwide. This study selected Chongqing as the study case and employed propensity matching scoring (PSM) to evaluate BER's actual energy savings performance for families with different incomes. Furthermore, this study selected the cost payback period as the indicator to analyze the fairness of BER subsidy and tried to reallocate the limited subsidy.

Compared with existing studies, the two major contributions of this study are 1) evaluating the actual energy-saving performance of BER for families with different income levels; 2) reallocating current BER subsidy considering families' income. These contributions provide a valuable reference for how to develop a fair and effective subsidy system worldwide, which benefits reducing energy poverty and promotes wider BER in limited renovation funds.

The article is structured as follows: Section 2 summarizes the relevant literature. Section 3 details the data collection process used in this study, and explains the process of the PSM method and subsidy reallocation. Sections 4 present and analyze the empirical results of PSM and discuss the reallocation of subsidies for building energy retrofitting, respectively. Section 5 explains the policy implications of this study. Finally, Section 6 describes the main conclusion of this study along with recommendations for future studies.

2. Literature review

2.1. Study on the energy-saving performance of BER

Previous studies that analyzed the energy-saving performance of BER strategies were mainly based on engineering simulations and empirical analyses driven by actual building energy data. The 2009 ASHERE Handbook considers the former approach as a "forward" approach, wherein the equations describing the physical behavior of systems and their inputs are known with the objective to predict the output (ASHRAE, 2009). EnergyPlus, MATLAB/Simulink, and other software were employed by the "forward" approach.

However, some studies reported an obvious gap between an actual building energy consumption and its theoretical simulation (i.e., forward approach), mainly resulting from the uncertainties in the occupants' characteristics (Van Den Brom et al.). These studies suggest adopting actual building energy consumption data to analyze and diagnose the issues within a building. Statistical/regression methods (Pedersen, 2007) and machine (Bourdeau et al., 2019; Chen et al., 2022), and deep learning (Amasyali & El-Gohary, 2021) are usually applied. Among them, traditional statistical/regression methods usually are adopted to explain the relationship between building energy consumption and its variables (Pedersen, 2007). Existing studies have applied traditional statistical regression methods to evaluate the actual energy-saving performance of BRE strategies. For example, Ji et al. (2021) indicated that, in South Korea, a building energy efficiency certificate can save 3.5–26.4 % of the total residential natural gas consumption for heating. Wang et al. (2019) employed the PSM method to eliminate the interference of covariables, and confirmed that Building Energy Efficiency Standard (BEES) can decrease the electricity consumption for heating and cooling (H&C) by 38–44 %. Khanna et al. (2016) confirmed that refrigerators with China Energy labels can reduce household electricity consumption compared with refrigerators without China Energy labels. Van den Brom et al. (2019) investigated the energy-saving performance of different BER strategies based on the actual energy consumption of the Netherlands. The authors pointed out that deep retrofit can save nearly 140 MJ/m^2 of natural gas per year. Notably, during the evaluation process, these models usually integrate other covariates to eliminate the interference of covariate uncertainty on the evaluation results. These covariates can be divided into four categories (Table 1) namely physical features of buildings (Khanna et al., 2016; Lee et al., 2020; Wang et al., 2019), surrounding environment (Novianto et al., 2022), occupants' behavior (Hu et al., 2016; Satish & Brennan, 2019), and occupants' characteristics (Brounen et al., 2012; Genjo et al., 2005; Huo et al., 2021a; Tran et al., 2021).

As a focus of this study, residential income is the one of most important driving factors for residential energy consumption. Specifically, increased income can lead to increasing demand for high lifestyles and entertainment, which are met by more household appliances

Table 1
Driving factors of residential energy consumption.

Covariates	Specific parameters	Refs.
Physical features of buildings	BEES/ Building energy efficiency certificate	Ji et al. (2021), Wang et al. (2019)
	Floor area	Gao et al. (2019), Wang et al. (2019)
	Energy efficiency of household appliance	Chen et al. (2010), Khanna et al. 2016, Wang et al. (2019)
Surrounding environment	Climate (HDD or CDD)	Huo et al. (2021b)
	Housing density	Tian et al. (2021)
Occupants' behaviors	Appliance utilization	Hu et al. (2016)
	Windows utilization	Hu et al. (2016), Wang et al. (2019)
Occupants' characteristics	Number of family members	Gao et al. (2019), Novianto et al. (2022), Ren et al. (2020), Tran et al. (2021)
	Age	Brounen et al. (2012), Novianto et al. (2022), Ren et al. (2020), Wang et al. (2019)
	Work statue	Brounen et al. (2012), Novianto et al. (2022), Ren et al. (2020)
	Income	Genjo et al. (2005), Huo et al. (2021a)

and longer appliance utilization periods, thus resulting in increased residential energy consumption (Genjo et al., 2005; Ren et al., 2020). For example, Genjo et al. (2005) indicated that residential electricity bills increase linearly with the residents' incomes. Pesantez et al. (2023) got different empirical results in Chicago case, showing that income had a little or negative impact on residential building consumption. However, they pointed out the negative impacts may result from a higher energy efficiency of household equipment and building envelope in high-income family.

In summary, previous studies have made significant contributions to assessing the impact of building characteristics and families' income on residential energy consumption. However, the model of existing studies only investigated the direct relationship between actual building energy consumption and two variables. The energy-saving performance of BER for families with different incomes remains unclear.

2.2. *Study on subsidy allocation of BER*

The availability of subsidies and costs are major obstacles to promoting BER (Choi et al., 2023; Jiang et al., 2022; Kim & Lim, 2021). Globally, the principle of subsidy allocation is based on a technique-related indicator such as building floor and adopted building energy efficiency techniques (Wiethe, 2022), while ignoring income. For example, in China, buildings that meet the technical regulation of BER standards can be allocated subsidies based on building floor area (MOHURD, 2012b). In the Netherlands, Investment Subsidy for Sustainable Energy and Energy Saving (ISDE) allocates subsidies for building owners who invest in heat pumps, solar water heaters, connection to a heat network, and insulation measures. The key calculation indicators of the ISDE comprise the techniques used, the project's initiation date, the minimum and maximum requirements, and the building's floor area. In Germany, subsidies for thermal renovation are awarded only to projects carried out to higher standards (Galvin, 2010). However, existing studies show that these subsidy allocations of BER are inefficient and unfair, and exacerbate energy poverty in poor households (Egner et al., 2021; Lekavičius et al., 2020; Rivers & Shiell, 2016). Specifically, Lekavičius et al. (2020) confirmed that, in Lithuania, the three wealthiest deciles (total of 10 deciles) make up approximately half of potential beneficiaries of residential energy technologies subsidy, while the poorest decile hardly benefits. Egner et al. (2021) also indicated the subsidy of BER was obtained by high-income families in Norway. Due to good affordability and quick cost recovery period (high-income families can save more energy since their total energy consumption is higher) (Nauleau, 2014; van den Brom et al., 2019), high-income families usually are more motivated to make BER. It may lead to the free-riding behavior of wealthy families (i.e., a family receives a subsidy, even though they would have implemented BER without subsidy) (Egner et al., 2021). Existing studies have shown widespread and high rates of free-rider behavior for BER, such as 50 % in Swiss (Studer & Rieder, 2019) and Canada (Rivers & Shiell, 2016), 40–85 % in France (Nauleau, 2014), and 92 % in Germany (Grösche et al., 2009).

Furthermore, these studies suggest the design of subsidies should consider the current situation of lower-income families and affordability issues to obtain an fair allocation of subsidies and to implement more energy-efficient building retrofits with a limited subsidies foundation (Lekavičius et al., 2020). Besides, some studies have tried to reallocate the subsidy of BER to improve efficiency and equitability. For example, to maximize the building energy-saving of Lyngby-Taarbæk in Denmark, based on the marginal cost of the energy saving of building Retrofits, Siddique et al. (2022) redesigned the subsidy of BER for buildings with different types and the age of construction. Zwickl-Bernhard et al. (2022) thought that owners are the investment decision-maker of BER but are not impacted by increasing energy price, while the tenants are impacted by increasing energy price and have no decision-making power to conduct BER. They attempt to allocate certainty subsidy pool to owners and tenants by minimizing total governance's costs including investment grants and subsidy payments. However, few studies have attempted to reallocate the subsidy of BER to different income groups.

Based on the above literature, this study has two major contributions: 1) investigate the actual energy-saving performance of BER for families with different income levels; 2) reallocate the current subsidy of BER considering the families' income. These contributions fulfill two study gaps shown in the literature review and can provide a valuable reference to evaluate the actual energy-saving performance of residential BER and benefit policymakers in formulating fair and efficient subsidy policies.

3. Method

3.1. *Case background and study framework*

This study selected Chongqing as the study area located in Hot Summer and Cold Winter areas (HSCW) in China. China has provided subsidy support for HSCW since 2012 to reduce H&C energy consumption. The scope of funds includes three terms: external door and windows, exterior shading systems, and exterior insulation systems (MOHURD, 2012b), indicating the BER of Chongqing only influences household energy consumption for heating and cooling. There are two main reasons for our selection of Chongqing as a study area: (1) Chongqing locates in HSCW. Compared with the cold or severe cold area in China that adopt central heating (paying a one-time heating fee on floor space rather than heating consumption) (You, 2024), the heating consumption of HSCW areas is flexible and easily affected by temperature, energy cost, and families' incomes. (2) Most families in Chongqing use electric appliances for heating and cooling, and their household energy consumption data only include electricity, indicating the H&C energy consumption can be split out by daily electricity consumption and temperature.

There are few cases of BER for mid and low-income families. According to the BER standard (JGJ/T 129–2012), the values of the technique indicators in BER follow the BEES (for new residential buildings) promoted in the same periods (MOHURD, 2012a). Chongqing currently adopted the BEES with a 65 % energy-saving rate (65 %-BEES, DBJ50–071–2020). Therefore, this study selected 65 %-BEES as benchmark for actual energy-saving performance of BER.

This study tries to provide a research framework for establishing a subsidy system considering families' income, which can be replicated worldwide. Specifically, the research framework has two steps.1) evaluating the energy-saving performance of BER for different income groups, and this study achieves this step according to evaluating the energy-saving performance of 65 %-BEES by a PSM method. 2) calculating the dynamic cost payback period of different income groups based on evaluation results, BER cost, energy prices and initial subsidy. And optimize subsidy allocation until the dynamic cost payback periods are the same for all income groups (Fig. 1).

3.2. *Evaluating the actual energy-saving performance of BER*

Due to the data limitation and similar indicator in building energy efficiency and BER, this study regards the performance of 65 %-BEES as the benchmark of BER. Traditionally, testing the actual energy-saving of BEES determines the energy consumption gap in a building before and after implementing specific standards. However, the pre-and post-standard energy consumption data for the same building are rarely available (referred to as "missing data"). Therefore, this study selected the PSM method to build counterfactual samples (Rosenbaum, 2002). Based on different covariables, the PSM method can match the treatment group (buildings with 65 %-BEES) with the control group (buildings without BEES, with similar co-variables as those in the treatment group). As listed in Table 1 and data accessibility, this study selected other control parameters (Table 2). Besides, the sample buildings in this study were

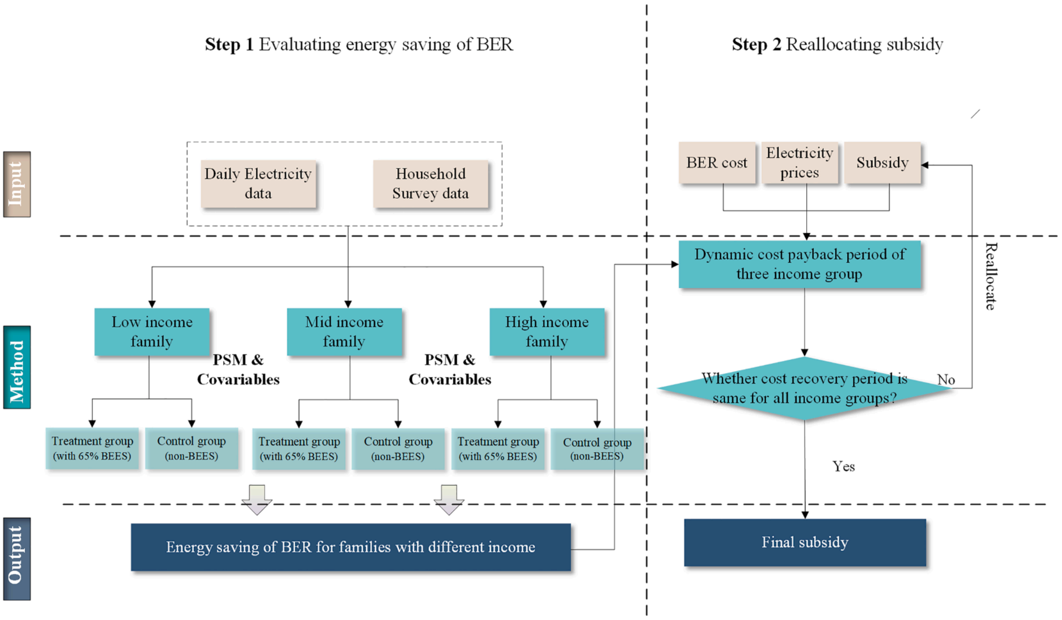

Fig. 1. Study framework.

Table 2
Definition of different variables.

Parameters category	Specific parameters	Description
Physical features of buildings	EEL	Follow China's energy label of equipment (1 = highest level, 3 = lowest level).
	ACs	Number of air conditioners
	EHs	Number of electricity heaters
	Area	Floor area of the building (m^2)
	Floor	Floor of building
Occupants' characteristics	Population	Number of family members
	Income	Families' income (1 = 〈 60,000; 2 = 60,000–120,000; 3 = 〉 120,000.
Occupants' behaviors	Daily period (heating or cooling)	Heating and cooling period in a day (hour)
	Temperature setting (heating or cooling)	1 = > 27 °C; 2 = 26 °C; 3 = 25 °C; 4 = 24 °C; 5 = 23 °C; 6 = < 22 °C
	Windows utilization	1 = Close windows before heating or cooling; 2 = Open windows when heating or cooling.

Note: Table 2 has 12 covariables. Daily period and Temperature setting include heating and cooling conditions.

located close to each other. Therefore, the interference of the surrounding environment was excluded, such as temperature and humidity.

Furthermore, to investigate the actual energy-saving rate of 65 %-BEES (BER) for families with different incomes, this study categorized the families into three income groups (high-, mid-, and low-income groups). Meanwhile, this study set a comparisons in each income group to calculate the energy-saving of 65 %-BEES (BER).

Rosenbaum (2002) first proposed the propensity score matching method. The method builds a counterfactual inference model and considers all converts as covariables, which are then input in the propensity scores to reduce dimensionality. The core idea of the method is to identify a control group, with the covariables being as similar as possible, to minimize the bias derived from covariables. When the distribution of covariables between the treatment and control groups is balanced, the gap between the treatment and control groups is the average treatment effect. Referring to the study of Shao et al. (2022), this study selected the following regression models to assess the actual energy savings performance of the two BERs:

$$Y_j = \varepsilon_j + \alpha BER_j + \beta X_j, \tag{1}$$

where Y_j represents the H&C electricity consumption intensity (*HCECI*, kWh/m^2) of a building *j*. BER_j is a dummy variable, indicating that building *j* has adopted BER; $BER_j = 1$ indicates that the building with BER is a treatment group, whereas $BER_j = 0$ indicates no adaptation of BER (the control group). β is regression coefficient of observed covariables. X_j is the other observed covariable, which may potentially impact the *HCECI* of building *j*. ε_j is a bias. α represents the impact of adopting BER on *HCECI*. The PSM method provided by Rosenbaum (2002) is the conditional probability of assignment to a particular treatment given a vector of observed covariates. This study adopts the average treatment effect on the treatment (*ATT*) to the actual energy savings effect of the 65 %-BEES (Eq. (2))

$$ATT = E\left\{E\left[Y_{1,j}\middle|P(X_j), BER_j = 1\right] - E\left[Y_{0,j}\middle|P(X_j), BER_j = 0\right]\right\}. \tag{2}$$

where *ATT* is measured as the absolute change of *HCECI*. $BER_j = 1$ and $BER_j = 0$ represent adopt 65 %-BEES and Non-BEES, respectively. $P(X_j)$refers to the propensity score of observable characteristics X_j in this study.

Referring to the guidance of Caliendo and Kopeinig (2008), this study conducted a PSM method following above steps: (1) calculating propensity score based on 12 covariables. Existing studies have proposed two standard probability methods (i.e., logit and probit) to establish propensity score. Lechner (2001) finds little difference between the performances of the two models. Logit model is easily to be calculated and explained. Thus, we selected the logit model to estimate the propensity score. (2) matching treatment group with control group according to the closeness of their propensity score. The common match methods included kernel, radius, and nearest neighbor matching. Since the performance of each matching method depended on specific study samples, to ensure the effectiveness of the matches, this study tested three matching methods and selected the results having the highest significance. Besides, bootstrapping methodology is used to evaluate the standard error influencing the estimate of the standards impact. (3) checking the overlap and region of common support. According to the overlap assumptions of PSM, to ensure matching equality and that the propensity score value ranges of the treatment and control groups are similar, we deleted the observations whose propensity score was less and more than the minimum and maximum values in the opposite group, respectively. (4) Sensitivity analysis on hidden bias. PSM method is based on conditional independence assumption. This study employed Rosenbaum's bounds (Rosenbaum, 2002) to evaluate the impact of unobservable characteristics on the selection process and matching analysis (see in Section 4.1.3).

3.3. Reallocating the subsidy of BER

Based on the evaluation results, we employed an optimal method to reallocate the subsidy. in this study, we regarded all existing buildings without BEES as potential energy retrofit objects. This study assumed that the renovation must meet the limitation of 65 %-BEES after energy retrofit. Overall, the subsidy funding ($SF_{overall}$) was calculated using Eq. (3), as shown below:

$$SF_{overall} = A_{overall} \times \overline{SF} \tag{3}$$

where $A_{overall}$ represents the overall floor area of the potential energy retrofit building. $\overline{SF}$ represents the average energy retrofit subsidy and equals 25 yuan/unit floor area (MOHURD, 2012b).

Thereafter, using Eq. (4), we analyzed the reallocated energy retrofit subsidy for the three income groups ($i =$ high-, middle-, or low-income), as follows:

$$\overline{SF} = \sum_{i} r_i \times SF_i, \tag{4}$$

where r_i represents the proportion of the retrofit buildings' floor area for different income groups i with respect to the overall retrofit buildings' floor area, derived from the household survey data in Section 3.4. In this study, the r_i of high-, middle-, and low-income was 43.61, 43.38, and 13.01 %, respectively. SF_i represents the energy retrofit subsidy unit floor area enjoyed by the income group i after the reallocation of the subsidy.

To ensure that the subsidies were distributed fairly, all income groups needed to have the same dynamic cost payback periods (*DCPP*). Therefore, this study could establish the following constraint and objective functions:

$$\min \sum_{i \neq j} \left(DCPP_i - DCPP_j\right)^2$$

$$s.t. \left\{ \begin{array}{c} \sum_{i} r_i \times SF_i = \overline{SF} \\ SF_i \geq 0 \end{array} \right\} \tag{5}$$

where $DCPP_i$ and $DCPP_j$ represent the dynamic energy retrofit payback periods of income groups i and j, respectively. To calculate the dynamic cost payback periods, the net present value of yth year (NPV_y) was calculated Eq. (6), and $DCPP_j$ can be calculated by Eq. (7).

$$NPV_y = Cost - Subsidy - \sum_{t=0}^{y} \frac{P \times saving_t}{(1+k)^t}, \tag{6}$$

$$DCPP = t_{NPV>0} - \frac{NPV_{t_{NPV>0}}}{\frac{P \times saving_{t_{NPV>0}}}{(1+k)^{t_{NPV>0}}}}, \tag{7}$$

where *Cost* represents the BER cost for unit area. Based on a few practical cases, this study obtains average energy retrofit cost unit area in the HSCW areas of the country (42.39 yuan/m^2). Although, initial difference in house may cause the difference in retrofit cost. In practice, due to lacking professional skill, assessing houses' initial condition and further deciding the specific BER cost, is very difficult for government staff. To facilitate practical implementation, we selected a uniform cost in the modeling process. k represents the discount rate and is set at 8 %. P represents the electricity prices and is set at 0.57 yuan/kWh, acquired from the Chongqing Bureau of Commodity Prices; $t_{NPV>0}$ represents the first year with positive *NPV*. $saving_t$ represents the H&C electricity energy savings of 65 %-BEES in Section 3.2. Due to the heating demand being low in Chongqing, we assumed H&C electricity consumption and *Saving* of each group still keep an increasing trend. Referring to existing studies (Tang et al., 2021; Wang et al., 2023), we fitted a logistic function between H&C electricity energy savings and income (Eq. (8)). Specifically, based on EnergyPlus software and maximum H&C utilization behaviors in Chongqing (data from household survey of Zheng & Wei, 2016), we stimulated upper limit of $saving_t$ (10.24 kWh/m^2, Table S1 in Supplementary material). Combined with the upper limit and the results of PSM, we fitted a logistic function.

$$Saving_t = \frac{(10.24 - c)}{1 + a \times e^{-b \times income_t}} + c \tag{8}$$

where $income_t$ represents the income of each group. Referring to the historical statistic data, we assumed that $income_t$ will increase by 9 % per year. a, b and c are fitted coefficients, and equal to 316.9128, 4.0883 and 3.1748, respectively.

Besides BER subsidy and energy saving happen at pre- and post- BER stage, Thus, this study assumes that BER subsidy only determines whether residents adopt BER, not effect heating and cooling behavior of residents. Thus, BER subsidy reallocation doesn't affect energy saving performance. where $t_{NPV>0}$ represents the first year with positive *NPV*.

3.4. Data collection

Data collection was supported by the Chongqing Housing and Urban-Rural Committee, and State Grid Chongqing Electricity Power Company (Table 3). The data were divided into two parts: The first included a household survey, which was designed based on Table 2. The content of the questionnaire is provided in the Supplementary material, and mainly includes the building characteristics, and residents' behavior and characteristics. The survey covered nine main districts of Chongqing.

According to household survey data, high-rise buildings are a major residential building type in Chongqing, accounting for nearly 81.8 % of the total buildings in the region. Apartments account for 13.9 %, and 2.0 % of all the buildings in the region consists of villas and semi-detached houses. To eliminate the bias caused by building type, this study did not consider villas or semi-detached houses. For heating and cooling, almost all the residents used air conditioners, with only two adopting natural ventilation methods. For heating, only 14 residents used non-electric methods/equipment, such as gas-fired or coal-fired boilers. Due to only having electricity energy consumption data, this study did not consider the residents who adopted no-electrical heating or cooling, and split the cooling and heating energy consumption using the household electricity consumption data.

The second part included the household electricity consumption data derived from the State Grid Chongqing Electricity Power Company.

Table 3
Data sources.

Type	Method	Sources
Household Characteristics	Questionnaire is shown in Supplementary documents	Household Survey
Daily household electricity consumption	Heating and cooling consumption splitting (Huo et al. 2021a)	State Grid Chongqing Electricity Power Company
Cost of building energy retrofit	–	Case collection
Subsidy of building energy retrofit	–	Implementation Opinions on Promoting Energy-saving Renovation of Existing Residential Buildings in Hot Summer and Cold Winter Areas (MOHURD, 2012b)

Since the electricity meter measures the overall electricity consumption of a family/house and cannot differentiate between the end-user services, this study extracts the electricity consumption intensity of household heating and cooling (*HCECI*) based on the method of Huo et al. (2021a). According to the BEES of Chongqing, we divided the household electricity consumption (E) of Chongqing into three seasons (Eq. (8)): winter season (E_{win}, from 1st December to next 28th February), summer season (E_{sum}, 1st June to 30th September) and other seasons (E_{other}, remaining season).

$$E = E_{win} + E_{sum} + E_{other} \tag{8a}$$

E_{win} concludes heating ($E_{heating}$) and other consumption, E_{sum} concludes cooling ($E_{cooling}$) and other consumption, and E_{other} only concludes other consumption. We assumed the daily other consumption intensity is same in all year, and further split $E_{heating}$ and $E_{cooling}$ from E_{win} and $E_{cooling}$, respectively.

$$E_{heating} = E_{win} - \frac{E_{other}}{D_{other}} \times D_{win} \tag{9}$$

$$E_{cooling} = E_{sum} - \frac{E_{other}}{D_{other}} \times D_{sum} \tag{10}$$

where D_{other}, D_{sum}, and D_{win} represent the periods of other, summer and winter seasons, respectively. *HCECI* can be calculated by Eq. (11).

$$HCECI = \frac{E_{heating} + E_{cooling}}{A} \tag{11}$$

where A represents the floor area of building.

4. Results and discussion

4.1. Actual energy savings performance of BER

4.1.1. Data description

Fig. 2a portrays the distribution of the BEES. The buildings with 65 %- BEES accounted for a larger proportion (66 %) compared with the buildings without non-BEES (34 %). Notably, in Fig. 2b, the buildings that did not adopt the BEES had an electricity consumption unit area of 28.01 kWh/m^2, whereas the building having 65 % BEES had a lower electricity consumption unit area (24.85 kWh/m^2). For the H&C electricity consumption unit area, the 65 %-BEES could reduce the energy consumption for H&C by 1.90 kWh/m^2 compared with non-BEES. The actual H&C electricity savings performance was lower than that expected by the simulation (65 % for H&C energy savings). That may be due to the differences in the residents' practical and theoretical energy consumption behavior.

In engineering simulation, the lifestyle of H&C was "full-place" and "full-time". Specially, BEES of Chongqing requires, that engineering simulation calculation needs cover the entire building, and adopt 18 ℃ and 26 ℃ throughout the day in winter and summer, respectively (5.0.7 in DBJ50–071–2016). While the survey data indicated that the practical lifestyle of H&C was "part-time" and "part-place.". As shown in Fig. 3, 53 % of families used air conditioning, when they felt very cold or hot; 34 % would turn on air conditions when they felt cold or hot, and only 13 % would turn on air conditions when they felt slightly cold or warm (Fig.3a). In summer, the mean of temperature setting is 25.15℃ (Fig.3b), most of families preferred to set 25 ℃ (41.5 %). and 26 ℃ (32.7 %). Notably, almost all families stated that they turned on the air conditioning when all family members were in one room, or one person existed in the room. Meanwhile, due to work hours or other entertainment activities, the H&C was not "full-time" and "full-place" in practice.

Fig. 4a portrays the distribution of the family incomes. The mid-income families (income range of 120,000–60,000 yuan) accounted for the largest proportion (41 %), followed by the low- (39 %) and high-income (20 %) families. The electricity consumption unit area of different income levels is shown in Fig. 4b. Particularly, this study observed that the higher the income, the higher their H&C electricity consumption unit area. Specifically, the H&C electricity consumption unit area of the high-income families was 1.73 kWh/m^2 more than the low-income families (8.49 kWh/m^2); this gap was mainly caused by the higher H&C demands of high-income families.

Moreover, this study also calculated the mean of the H&C electricity consumption unit area across by families' incomes and the adopted BEES (Fig. 5). As shown in Fig. 5, the energy savings performance was different for different income levels, although these family adopted the same BEES. In particular, the high-income families owned more H&C electricity-saving performance unit areas. According to 65 %-BEES, the H&C electricity-saving performance unit area of the high-, mid-, and low-income families was 3.73, 2.45, and 1.15 kWh/m^2, respectively.

The disparity of energy-saving is related to absolute household energy consumption. Table 4 shows the mean of other covariables in different income groups. Generally, the high-income group preferred to a higher frequency and longer utilization of heating and cooling. For appliance selection, high-income families usually own more electric heaters (0.46 units/family) and air conditioners (3.24 units/family) compared with low-income families (0.42 and 2.85 units/family). And heating and cooling appliances in high-income families are more effective. Meanwhile, the utilization behavior of the high-income group means higher heating and cooling consumption. Compared with mid and low-income groups, high-income group preferred to "open windows when heating or cooling", "lower temperature settings in summer", "higher temperature settings in winter", and "longer utilization period".

4.1.2. Energy savings by building energy efficiency standards for families of different income levels

The actual H&C electricity savings performances of the 65 %-BEES

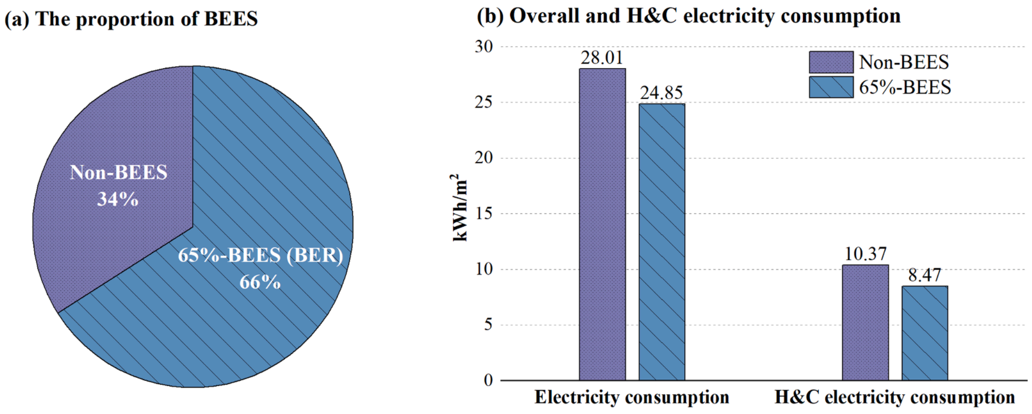

Fig. 2. Distribution of buildings by energy efficiency standards.

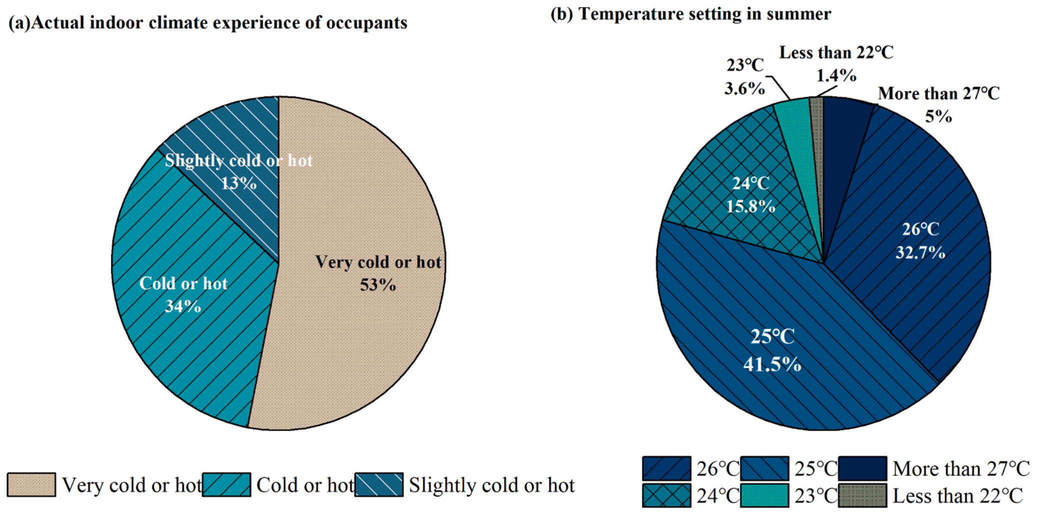

Fig. 3. Actual indoor climate experience of occupants while using the air conditioner.

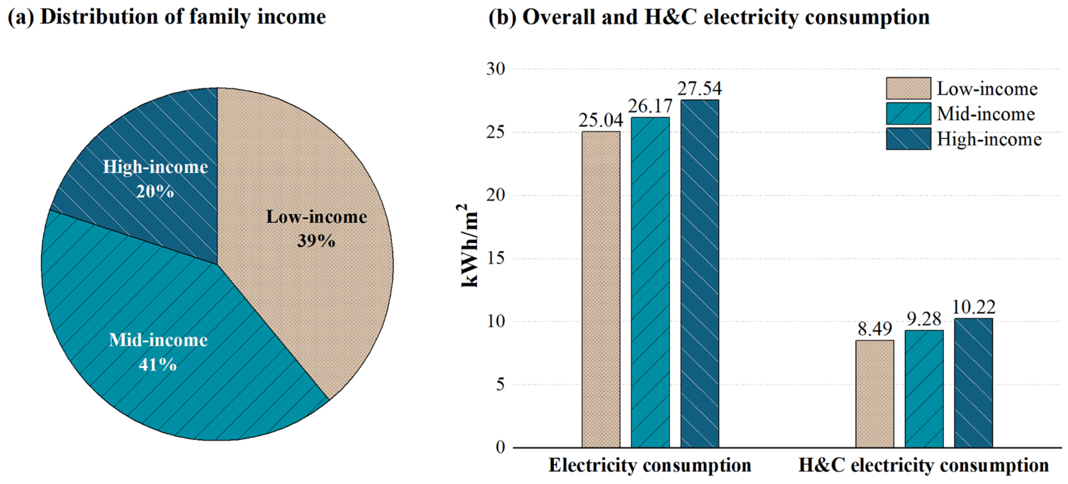

Fig. 4. Distribution of family income and electricity consumption.

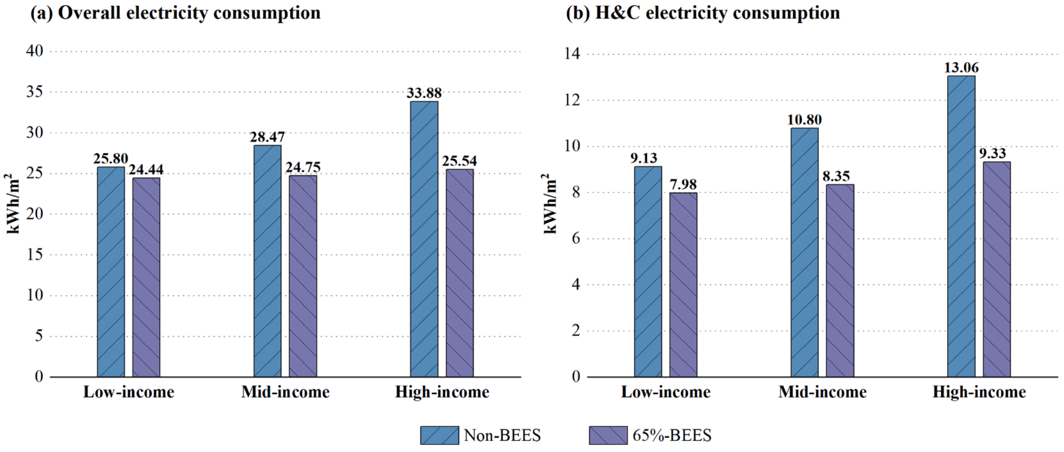

Fig.5. Heating and cooling electricity consumption across families' incomes and BEES.

are listed in Table 5. The *ATT* of 65 %-BEES was significant, at a 1 % significance level. Notably, our results indicated that adopting the 65 %-BEES can reduce the H&C electricity consumption by nearly 30 % (4.48 kWh/m^2), compared with the buildings without BEES. The actual H&C electricity savings rate calculated by PSM was higher than that directly calculated by the mean, indicating that other covariables have influence on the energy-saving of BEES and are evenly distributed in overall simple. Therefore, to meet the assumption in Section 2.1 (i.e.

Table 4
Mean of covariables in different income group.

Covariables	Impact	High-income	Mid-income	Low-income
EEL	(+)	1.61	1.63	1.67
ACs	(+)	3.24	3.12	2.85
EHs	(+)	0.46	0.51	0.42
Daily period (Heating)	(+)	2.51	2.08	2.22
Daily period (Cooling)	(+)	7.84	7.81	7.30
Temperature setting (Heating)	(+)	3.14	3.10	3.07
Temperature setting (Cooling)	(-)	2.89	3.01	3.01
Windows utilization	(+)	1.93	1.74	1.57

Note: Impact represents the expected impact of covariables on household energy consumption and energy consumption. The descriptions of covariables are show in Table 2.

Table 5
H&C electricity savings performance of BEES.

Group	Treated	Controls	Difference	S.td	P value
Overall	8.65	13.14	−4.48	0.86	0.000***
Low-income	8.09	11.34	−3.25	0.99	0.001***
Mid-income	8.25	12.21	−3.96	1.18	0.005***
High-income	9.77	17.13	−7.36	2.54	0.007***

using energy-saving performance of 65 %-BEES as the benchmark of BER) and create a counterfactual BER sample, PSM method is necessary to match control group with treatment group and eliminate the gap of covariables for different income groups. Notably, actual energy-saving performance of BER is lower than the values presupposed by 65 %-BEES. According to building engineering simulation, 65 %-BEES expects to achieve the 65 % saving target through the improvement of the U-values of the building envelope, energy efficiency of H&C equipment and assumed occupant's lifestyle (MOHURD, 1995). The results indicated that there is an obvious gap between engineering simulation and practice, especially for occupant's lifestyles. Engineering simulation usually assumes higher utilization (e.g. occupant period and space) of heating and cooling (Wang et al., 2019). Therefore, to establish an equitable subsidy and complete the BER standard, it is necessary to evaluate the actual performance of BER based on actual energy consumption data.

Table 5 summarizes the actual H&C electricity savings performance of the 65 %-BEES for the three income levels. *ATT* was significant, at a 10 % significance level. There was a significant difference in the energy savings of different income levels. Generally, the higher the income level, the higher the H&C electricity savings performance. Specifically, based on the 65 %-BEES, the H&C electricity savings unit area of the high-income families (7.36 kWh/m^2) was nearly 2.3 times of the low-income families (3.25 kWh/m^2). Considering that high-income families generally own houses with larger floor areas, they should be more responsible for reducing energy consumption and actively adopt BER and higher BEESs.

4.1.3. Robustness checks

Rosenbaum's bounds are used to evaluate the sensitivity of our estimates to hidden bias. A sensitivity parameter Γ is used to measure the degree of departure from the random assignment of treatments. Thus, attempting different values of Γ could show how the conclusion may change in the presence of potential unobserved confounders.

Table 6 lists the results of our sensitivity analyses for hidden bias. An observational study with $\Gamma > 2$ could consider a less heterogeneous study (Rosenbaum, 2002). According to the above standard, our results show that the estimates are insensitive to hidden bias. Take the group of low-income families as an example, the critical Γ value was 2.63 for the 65 %-BEES. Unobservable confounding factors for 65 %-BEES compared with non-BEES in the low-income group indicates the need to change the electricity consumption of buildings built with 65 %- BEES by approximately 2.63 times. The sensitive analysis results for mid-income and high-income groups could explain the observed similarly. The unobservable confounder could significantly impact electricity consumption to change inference, hence confirming our robust estimates.

Table 6
Rosenbaum bounds analysis for hidden bias.

Group	Γ	Sig+	sig-	CI+	CI-
Overall	3.68	0.0000	0.051	−8.845	0.0071
Low-income	2.63	0.0000	−0.051	−7.092	0.0027
Mid-income	2.71	0.0000	0.050	−6.777	0.0007
High-income	4.32	0.0000	0.050	−14.852	0.0002

In summary, Section 4.1 discussed the energy-saving performance of BEES for families with different incomes, which responds to the first study issue.

4.2. Subsidy reallocation for BER

4.2.1. Current subsidy reallocation for BER

The results of subsidy reallocation for BER are shown in Fig. 6. a, b and c in Eq. (8) equal to 316.9128, 4.0883 and 3.1748, respectively. In the best optimize result, the error of objective function in Eq. (5) was 4.009E-7. Therefore, each income group's dynamic cost payback period after reallocation was assumed to be the same, and the reallocation adhered to the equity principle.

When all the buildings' owners received the same BER subsidy (25.00 yuan/m^2), the BER cost payback period of each income group differed. The cost payback period of the low-income group (16.84 years) and middle-income groups (6.61 years) is longer than high-income group (5.37 years). Therefore, BER has lower techno-economics for low-income group, that means the low-income group may has a lower motivation to conduct BER under currently subsidy policies. After carrying out the subsidy reallocation for BER, this study observed that the dynamic BER cost payback period of each income group was the same and less than 10 years (8.07 years). The results revealed that the low-income groups can significantly profit from subsidy reallocation. In particular, the BER subsidy of the low-income (32.57 yuan/m^2) will increase by 30.29 %. While, the BER subsidy for the high- (15.38 yuan/m^2) and mid- (20.27 yuan/m^2) income group decreased by 38.46 % and 18.91 %, respectively.

4.2.2. Sensitivity test on subsidy reallocation results

Furthermore, to test the impact of parameters (retrofit cost, retrofit subsidy, and electricity price) on subsidy allocation, a sensitivity analysis is employed by making each parameter grow by 5 % (Fig. 7).

As Fig. 7 shows, growth in a retrofit cost will increase the cost payback period from 8.07 to 10.07 years, discouraging all families from making BER. Meanwhile, to achieve a fair subsidy, growth in retrofit cost also requires low-income and high-income groups to receive a higher and lower subsidy, respectively. This indicates that for promoting wider BER, low-income and mid-income families must be considered. Growth in BER subsidy decreases the cost payback period, implying potential growth in BER motivation of residents. Although the increase in retrofit subsidy allows all groups to receive more retrofit subsidy, the share of each group has a few changes. Besides, growth in electricity prices has little impact on subsidies for each group. However, it decreases the BER cost payback period by nearly 10 %, which suggests that the government can facilitate the implementation of BER through reasonable energy price controls, such as step tariffs.

In summary, Section 4.2 reallocated limited BER subsidy and analyzed the sensitivity of reallocation results, which respond to the second study issue.

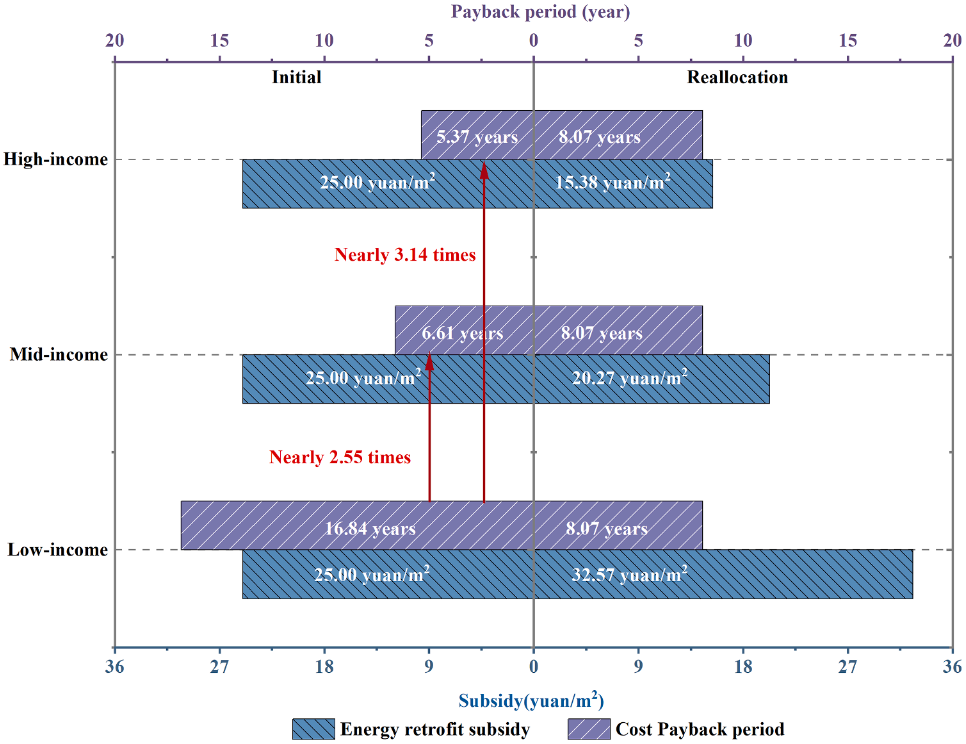

Fig. 6. Results of BER subsidy reallocation.

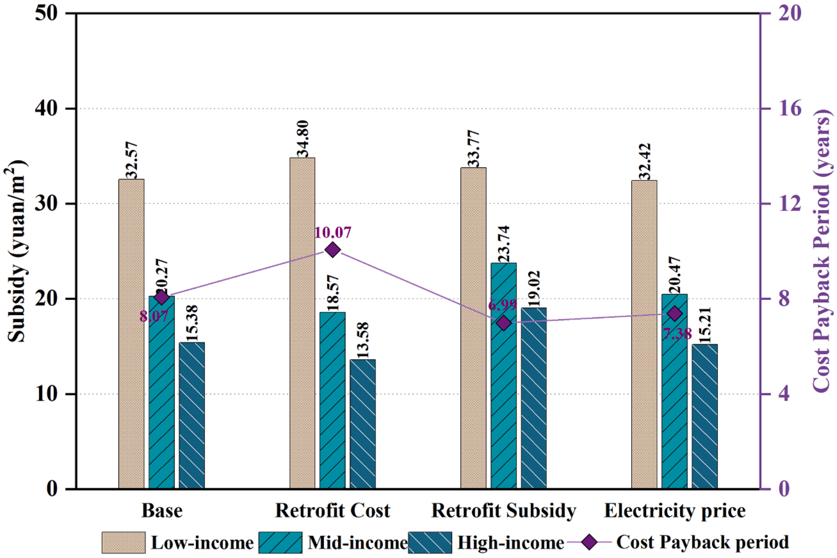

Fig. 7. Sensitivity Testing of subsidy.

5. Policy implications

5.1. *Developing a data-driven mechanism to evaluate building energy consumption*

The results of this study indicated that the actual energy savings performance was lower than the target value of the theoretical simulation model. The actual energy consumption data formed the basis to determine the effectiveness of building energy efficiency policies in China. China has established a system and platform of energy efficiency supervision for the commercial and public systems in 30 provinces. As a typical case, Shanghai launched a complete data monitoring platform for commercial and public buildings in 2017, covering an area of 92.08 million m^2. However, there is no platform and mechanism for regular survey on actual residents' energy data. Therefore, this study recommends a micro energy consumption database for future energy savings projects and actions in China (Yan, 2023). Similar to the Energy in Buildings and Communities Program proposed by the International Energy Agency, to collect the data related to actual building energy use, including building and occupant data (IEA, 1977), the Residential Building Energy Consumption Survey Database (EIA, 2020), U.S. Building Energy Codes Program (DE, 2016), and UK National Energy Efficiency Data-Framework (DBEIS, 2021). Besides, as the improve of people's living quality, initial income level may not match future condition. Regular survey on actual residents' energy data also facilitates to continuous updating of BER subsidy plan.

5.2. Development of subsidy and finance policies, while considering families' incomes

Cost is a significant obstacle to promoting higher building energy efficiency standards for new buildings and BER for existing buildings. Therefore, subsidies and finance policies can promote the acceptance of BER among families. However, this study indicates that subsidies and finance policies only considering technique-related indicators will cause the cost payback period of low-income families to be 2.5 times that of high-income families. Therefore, we recommend that China should clarify the actual energy savings of building energy efficiency policies in future energy savings projects and implementations and establish a tiered subsidy policy for different income levels. This way it will ensure the effective use of limited subsidy foundation. Furthermore, Santos et al. (2022) also highlighted that importance of subsidy programs that are tailored to needs and priorities of low-income and high-income group and the variations in investment behavior. Notably, this policy can have worldwide implications (Egner et al., 2021; Galvin, 2010; Lekavičius et al., 2020). For example, in the Netherlands, the Investment Subsidy for Sustainable Energy and Energy Saving (ISDE) formulates subsidies for investing in heat pumps, solar water heaters, connection to a heat network, and insulation measures. The calculation indicators of the ISDE mainly include adopted techniques, start date, minimum and maximum required, and the number of building areas.

6. Conclusion and future research directions

This study selected the buildings with 65 %-BEES to represent the buildings after building energy retrofit and evaluated the energy savings potential of building energy retrofit based on actual household electricity consumption data. Furthermore, based on the dynamic building energy retrofit cost payback period, this study discussed the limitations of the existing subsidy and carried out the reallocation of the energy retrofit subsidy. The main findings of this study are as follows:

(1) Building energy efficiency standards and energy retrofits can reduce energy consumption, despite their energy savings performance being lower than the theoretical simulation. Adopting 65 %- BEES (BER) can reduce 30 % of the H&C energy consumption.
(2) High-income usually has higher energy savings of BER. Specifically, the energy savings of high-income families was 7.36 kWh/m^2, nearly 2.3 times that of low-income families (3.25 kWh/m^2).
(3) The subsidy calculation carried out by only considering technology indicators was not equitable, causing the energy retrofit cost payback period of low-income families to be nearly 2.55 and 3.14 times that of the mid-income (6.61 years) and high-income (5.37 years) groups, respectively. Furthermore, this study suggests a subsidy of 32.42, 20.48, and 15.21 yuan/m^2 for low-income, mid-income, and high-income families, respectively.

This study has some limitations. First, because of the limitation of household survey samples, this study only established three income groups. Future studies should establish more income group division to improve the fairness of subsidy policies. Meanwhile, this study adopted splitting daily electricity data to obtain the heating and cooling electricity consumption. However, due to the residents' demand for other end-use services is dynamic in a year, the split data inevitably has some errors. To improve the accuracy of results, future studies should collect more detailed household energy data by installing meters for end-use services. Secondly, this study mainly focuses the impact of income on the energy-saving performance. Understanding the impact of other covariables plays an important role in completing BEES and BER standard and subsidy. Future studies will conduct other similarly study focusing on different covariables. Additionally, for the subsidy reallocation, this study simply considers the change of occupants' behavior and energy prices in the future. However, the occupants' behavior and energy prices are impacted by many factors. Future studies will integrate the forecasting the change of behavior and energy price into the model, and establish more comprehensive subsidies and finance policies.

CRediT authorship contribution statement

Kairui You: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Queena K Qian:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Weiguang Cai:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Xia Wang:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Henk Visscher:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization.

Declaration of competing interest

The author(s) declared no potential conflicts of interest for the research, authorship, and/or publication of this article.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2024.105317.

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