energies

Article

Retrofit Analysis of City-Scale Residential Buildings in the Hot Summer and Cold Winter Climate Zone

Yanfei Ji [1], Guangchen Li [1], Fanghan Su [1], Yixing Chen [1,2,*] and Rongpeng Zhang [2,3,*]

[1] College of Civil Engineering, Hunan University, Changsha 410082, China; jyf0316@hnu.edu.cn (Y.J.); guangchenli@hnu.edu.cn (G.L.); sufanghan@hnu.edu.cn (F.S.)
[2] Key Laboratory of Building Safety and Energy Efficiency of Ministry of Education, Hunan University, Changsha 410082, China
[3] School of Architecture and Planning, Hunan University, Changsha 410082, China
* Correspondence: yixingchen@hnu.edu.cn (Y.C.); zhangrongpeng@hnu.edu.cn (R.Z.)

Abstract: The rising energy consumption in residential buildings within the hot summer and cold winter (HSCW) climate zone, driven by occupants' pursuit of improved thermal comfort, necessitates effective energy conservation measures. This study established urban building energy models for 32,145 residential buildings in Changsha City, China, and conducted a comprehensive retrofit analysis of seven energy conservation measures (ECMs). Additionally, the study assessed the impact of residents' conscious energy-saving behaviors concerning air conditioner (AC) control. The research commenced by creating six baseline models representative of the diverse building stock. Identifying seven commonly used ECMs, the study examined the potential of each measure for enhancing energy efficiency. To facilitate the analysis, a dedicated toolkit, AutoBPS-Retrofit, was developed to efficiently modify the baseline model for each ECM. Furthermore, the investigation delved into the investment cost of implementing the ECMs and evaluated their simple payback year (PBP) and net present value (NPV). The results demonstrate that tailored retrofit plans are essential when addressing envelope improvements, varying according to building types and ages. Retrofits targeting lighting systems offer both promising energy savings and favorable economic viability, albeit subject to residents' preferences. Alternatively, upgrading the AC systems emerges as the most energy-efficient approach, yet the economic assessment raises concerns. The study's findings offer practical insights for governments seeking to establish effective carbon reduction goals and policies. Moreover, the research can assist energy-saving institutions, real-estate companies, and stakeholders involved in renovation projects by offering guidance in making informed decisions to enhance energy efficiency in city-scale residential buildings.

Keywords: residential buildings; building simulation; energy conservation measures; city-scale modeling; retrofit analysis

Citation: Ji, Y.; Li, G.; Su, F.; Chen, Y.; Zhang, R. Retrofit Analysis of City-Scale Residential Buildings in the Hot Summer and Cold Winter Climate Zone. *Energies* **2023**, *16*, 6152. https://doi.org/10.3390/en16176152

Academic Editors: Francesco Asdrubali, Weirong Zhang, Ning Li, Jian Dai and Ziwei Li

Received: 8 August 2023
Revised: 19 August 2023
Accepted: 22 August 2023
Published: 24 August 2023

1. Introduction

Energy saving in residential buildings has become highly valued by national policymakers worldwide, driven by both environmental concerns and the escalating demand for domestic energy. In the European Union, the residential sector is responsible for approximately 26% of the total energy consumption [1]. According to the China building energy consumption annual report, in 2021, the total building energy consumption amounted to 31%, with existing residential buildings in China constituting approximately 78% of the total buildings and contributing 17% to the country's overall energy consumption; however, a portion of these old residential buildings exhibits a noticeable disparity when compared to current energy-saving standards [2]. The 14th Five Year Plan for Building Energy Efficiency and Green Development proposes to complete the energy-saving retrofit of existing buildings with an area of over 350 million square meters by 2025. Therefore, the energy-saving retrofit of existing residential buildings is an important means to reduce building energy use and to achieve low-carbon goals [3].

Retrofitting and reconstruction stand as two alternatives for upgrading or replacing such structures. In response to this matter, Ahady and Peng [4,5] assert that retrofitting holds greater ecological and economic significance. Fleur et al. [6] studied the life cycle cost of energy retrofit, as well as the cost of building demolition and construction. The results show that building energy retrofit is a more cost-effective way. Gasper et al. [7] compared the impact of complete demolition and rebuilding of a detached residential building in Portugal on Life Cycle Energy. It was found that the Life Cycle Energy consumption of retrofit was significantly lower than that of rebuilding. Although energy-saving renovation has the advantages of reducing energy consumption and saving costs, there are also certain risks. The implementation of residential building retrofit faces many risks, such as homeowners and contractors [8,9], involving retrofit awareness, cooperation performance, opportunism, professional expertise, construction management, safety management, and maintenance, causing the slow retrofit process in the hot summer and cold winter (HSCW) zone of China [10]. The HSCW zone covers an area of 1.8 billion km^2, involving 14 provinces and 2 municipalities [11]. Due to extreme weather conditions, great demands for cooling in summer and heating in winter exist simultaneously, which brings a certain difficulty to constructing energy-efficient buildings in this region [12,13]. Only 70.9 million m^2 of retrofit projects were completed in the HSCW zone during the 12th Five-Year Plan period, a much slower rate than the northern region with 990 million m^2 [10]. Therefore, it is necessary to accelerate the implementation of residential energy retrofitting in China's HSCW zone while retrofitting existing buildings is an effective way. Real-estate investors are reluctant to bear additional costs for the hidden benefits of energy saving, and residents also consider renovation projects as an uncomfortable measure that delays their normal life. Almost all retrofit projects are government-led, and governments have to make a severe choice between energy-saving effects and investment costs [14]. The reasonable retrofit of existing buildings is the key, which can not only reduce building energy consumption but also have the advantages of low cost and high income [15].

Building energy modeling is widely used in retrofit analysis, especially for a single residential building that has always been researching hot spots. Huang et al. [16] conducted a passive energy-saving renovation on a high-rise residential building, reducing its cooling energy consumption by 8.7%. The payback period for the renovation cost is 18.4 years, and residents can profit from the remaining lifespan of the building. Short et al. [17] used the existing 23-story high-rise apartments in Hangzhou as an example to verify the feasibility of a low-carbon adaptation strategy of external shading and natural ventilation. Yao et al. [18] used a typical apartment in Chongqing, Changsha, and Shanghai as an example to conduct extensive parameter analysis on passive strategies such as building orientation, insulation, glass area, shading devices, air tightness, and natural ventilation. Qu et al. [19] carried out passive renovation of Victorian buildings in the late 19th century. The renovation methods included interior wall insulation, glass upgrading, and air tightness improvement. The best combination of these three retrofit measures can reduce primary energy consumption by 51.8%. Energy-saving retrofit can also use the global sensitivity analysis method, which selects the best retrofit scheme considering the change of parameters such as human behavior. Building energy consumption and carbon emissions are reduced by 26.4% after using this method [20]. Li et al. [21] proposed an energy comfort optimization model based on simulation and, combined with the response surface method, formed an excellent building renovation scheme. Through example verification, the scheme can save 4% of energy and improve the thermal comfort of the built environment. Lupíšek A et al. [22] applied an industrial building system with prefabricated modular elements to calculate the energy-saving potential of a representative Czech residential building. They found that the total energy consumption of Czech residential buildings could be reduced by 2.9%.

While the majority of research concerning building energy-saving retrofits is centered on individual buildings, a subset of scholars is inclined toward investigating building retrofits at an urban scale [23]. Wang et al. [14] established a set of procedures for developing an optimal energy-saving retrofit scheme in old residential buildings in Nanjing City. The optimal scheme can reduce 18.52% of residential building energy consumption in five central districts. Teso et al. [24] used the CityBES model to carry out energy-saving renovation of an urban area in Venice, respectively, taking four kinds of renovation measures for building envelope structures and heating boilers. The results show that the energy consumption and cost of urban buildings are reduced by 67% after the renovation. Deng et al. [25] proposed a new Automated Building Performance Simulation tool, combined with Geographic Information System data to calculate building energy use and then to upgrade the building's air conditioning system, photovoltaic power generation system, envelope structure, etc. The results show that energy use intensity can be reduced by 30.7% and that energy demand can be reduced by 18.5%. Adilkhanova et al. [26] considered combining the urban climate model, urban building energy consumption model, and actual data and applied a high albedo material to transform the building. The simulation results show that the urban temperature is reduced by 2.08 °C, and the building energy use is reduced by 7.7 kWh/m^2. Afshari [27] uses reanalysis data from the European Centre for Medium-Range Weather Forecasts, combined with the Standalone Urban Energy/Climate Model, to transform the city. This method reduces the cooling electricity demand by more than 40% and the heat island intensity by more than 25%. Mousavi et al. [28] proposed an intelligent energy comfort system for roof renovation of residential quarters by combining integrated machine learning and Taguchi design methods. The system can increase thermal comfort time by 12.8% and reduce energy consumption by 14%. Tsang et al. [29] predicted the energy consumption for space heating and cooling and the thermal comfort of individual flats, single buildings, and a city in Chongqing. They examined the energy consumption of seven energy-saving measures and three air conditioning operation modes. Studying the energy-saving potential of residential buildings on a city scale is of great ignificance.

Prior research has furnished valuable insights into assessing the energy-saving potential of urban residential buildings. However, the abundance of ECMs for residential settings remains less comprehensive, and the degree of automation of model establishment and retrofit is insufficient. Furthermore, there exists a notable dearth in the practice of conducting pre-renovation and post-renovation economic analyses concerning urban residential buildings. Moreover, city-scale building energy simulation reveals a duo of challenges: Firstly, the endeavor necessitates substantial computational resources and computing time [30]. Secondly, the execution of urban energy simulations frequently entails juggling multiple software packages and necessitates cross-platform operations [31]. References [30,31] Aiming to obtain effective city-level carbon reduction goals and policies, this specific case study of Changsha City needs to overcome the difficulties of collecting and processing city-scale data, which is the most fundamental difference from the simulation of individual buildings.

To bridge these gaps evident in prior investigations, we have formulated a framework for executing retrofit analysis of city-scale residential buildings. Firstly, seven distinct ECMs have been proposed by accounting for three fundamental facets of residential buildings, including envelope structures, lighting systems, and AC systems. Secondly, building upon the foundation of our prior research on AutoBPS as a solution for rapid simulation and cross-platform operations involving massive data [25], our present study undertakes an extensive enhancement of the retrofit functionality, specifically through the development of AutoBPS-Retrofit. This dedicated tool enables the seamless implementation of ECMs with a high degree of automation and high speed of calculation. Subsequently, an economic analysis of the retrofitting of city-scale residential buildings is carried out, facilitated by AutoBPS-retrofit. In intricate detail, against the backdrop of policy support and the demonstrated advantages of retrofitting over reconstruction, this paper directs its focus toward the analysis of energy consumption within a pool of 32,145 mid-rise and high-rise apartments situated in Changsha. This study encompasses the examination of energy consumption under seven distinct ECMs, diverse AC operation strategies, and comprehensive economic analysis. The primary objective of this paper is to offer valuable references for governments in formulating effective carbon reduction goals and policies. Furthermore, the research aims to offer pivotal insights and guidance to energy-saving institutions, real-estate enterprises, and other pertinent stakeholders involved in renovation endeavors.

2. Methods

In order to formulate expansive building energy-saving retrofit strategies that encompass both energy-saving efficacy and economic advantages, the research workflow is visually depicted in Figure 1. Initially, baseline models are called from AutoBPS based on input data, including building type, vintage, and climate zone entered by the user. Subsequently, the retrofit project is formulated to meet specific requirements, with seven ECMs available, covering exterior walls, roofs, windows, external shadings, air sealing, lighting systems, and AC systems. The baseline models can be obtained if the users do not choose any ECM. Following the development of both the baseline models and retrofit models, EnergyPlus is employed as the simulation engine to calculate the energy use intensity (EUI), forming the basis for evaluating energy-saving effects. Lastly, the payback period (PBP) and net present value (NPV) serve as indicators to assess the economic feasibility of the selected ECMs.

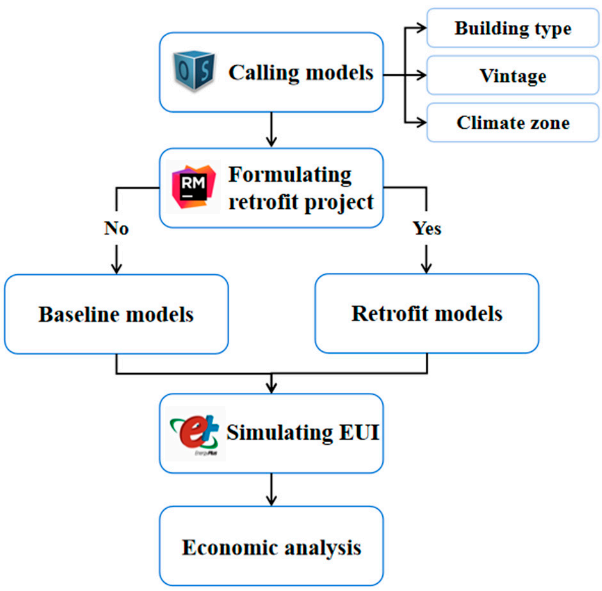

Figure 1. Research workflow for large-scale building energy-saving retrofit schemes.

2.1. Data Collection and Building Classification

Changsha, located in the central part of China, is the capital of Hunan Province. The climatic condition of Changsha is typical of hot summer and cold winter. The climate zone of it is categorized as GBCZ-3B, referring to the Uniform Standard for Design of Civil Buildings (GB50352-2019) [32]. According to a previous study, Deng and Chen [33] collected building information on existing residential buildings in Changsha, including 10,377 high-rise apartments and 21,768 mid-rise apartments in Yuelu District, Kaifu District, Furong District, Tianxin District, and Yuhua District. These residential buildings in five districts of Changsha as the main urban area were selected as the case study area.

According to the type of building and the year built, the target buildings can be divided into 18 categories. The type of building can be divided into high-rise apartments, mid-rise apartments, and low-rise apartments. According to the year built, it can be divided into before 2001, from 2001 to 2010, and after 2010. According to the function, the building can be divided into residential buildings and commercial buildings. According to the above classification criteria, the information and classification of 53,591 existing residential buildings are summarized, as shown in Table 1.

Table 1. Classification of 18 types of buildings.

Case	Building Type	Year Built	Footprint (Million m^2)	Number of Buildings
1	High-rise residential	Pre-2001	1.6	2626
2	High-rise residential	2002–2009	2.1	2991
3	High-rise residential	2010 and After	2.7	3533
4	High-rise residential–shops	Pre-2001	0.2	297
5	High-rise residential–shops	2002–2009	0.5	483
6	High-rise residential–shops	2010 and After	0.4	447
7	Mid-rise residential	Pre-2001	4.7	8441
8	Mid-rise residential	2002–2009	3.5	6631
9	Mid-rise residential	2010 and After	2.4	4306
10	Mid-rise residential–shops	Pre-2001	0.8	1147
11	Mid-rise residential–shops	2002–2009	0.7	880
12	Mid-rise residential–shops	2010 and After	0.3	363
13	Low-rise residential	Pre-2001	2.2	5735
14	Low-rise residential	2002–2009	2.2	6530
15	Low-rise residential	2010 and After	2.8	7586
16	Low-rise residential–shops	Pre-2001	0.5	620
17	Low-rise residential–shops	2002–2009	0.4	484
18	Low-rise residential–shops	2010 and After	0.5	491

This study focuses on the retrofit effect of buildings with different vintages and building types under different ECMs. Given the limited availability of energy-saving renovation scenarios for low-rise apartments, this study exclusively focuses on analyzing high-rise and mid-rise apartments spanning varying construction periods, and apartments with or without shops are merged according to the number of building floors. The information on the selected six buildings is summarized in Table 2.

Table 2. Classification of 18 types of buildings.

Case	Building Type	Year Built	Number of Buildings	Footprint (Million m^2)	Floor Area (Million m^2)
1	High-rise apartment	Pre-2001	2923	1.88	17.4
2		2001–2010	3474	2.59	34.9
3		2010 and After	3980	3.09	56.0
4	Mid-rise apartment	Pre-2001	9588	5.47	28.8
5		2001–2010	7511	4.15	22.6
6		2010 and After	4669	2.73	15.2

2.2. Baseline Model Establishment

The establishment of baseline models involves the generation of both geometric and energy models. The geometric models' spatial layout draws reference from DOE prototype models. OpenStudio-Standards is employed to incorporate properties such as building envelopes and schedules, aligning them with Chinese standards. Geometry models are structured in the OpenStudio model format using the SketchUp Plug-in, while the energy models are assembled through OpenStudio and EnergyPlus. After clarifying the above mechanism, the establishment of the baseline models also relies on the user input information, including building type, climate zone, and vintage. In this study, 32,145 residential buildings in Changsha were regarded as target buildings. They were divided into two building types, those above three floors but below seven floors are called mid-rise apartments, and those above or equal to seven floors are called high-rise apartments. According to the building type inputted, AutoBPS will generate the geometric models referring to DOE prototype models. The climate zone is 3B, and the standard adopted in this area is 'Design standard for energy efficiency of residential buildings in hot summer and cold winter area' (JGJ134). According to the time nodes of JGJ134-2001 [34] implemented in 2001 and JGJ134-2010 [35] implemented in 2010, it is divided into three vintages: built before 2001, built between 2001 and 2010, and built after 2010. The standard library is also filled by referring to the limit values in JGJ134, and OpenStudio will endow the energy model with settings that comply with local standards. Therefore, six kinds of baseline models are generated. The operating settings of AC are as follows: The indoor temperature is set at 26 °C in summer and 18 °C in winter. On the schedule of work and rest, the turning on or off of lights and air conditioning depends on the worker's home time [36]. It is set to off at 18:00–8:00 and on the rest of the time.

2.3. ECM Identification

This section covers some literature reviews of commonly used ECMs, as shown in Table 3. It can be seen that all of them involve the retrofit of envelopes because building envelopes play a significant role in achieving energy-efficient buildings [37]. For exterior walls and roofs, the method of adding insulation layers is adopted for retrofitting. Commonly used materials include expanded polystyrene (EPS) and extruded polystyrene (XPS), but EPS is more popular because it offers similar thermal performance at a low price. Shading systems could help reduce the cooling load by cutting down solar heat gain, which means that adding shading systems is an effective retrofit measure. Compared with internal devices, external shading is regarded as a priority option. The most common external shading devices are overhangs, requiring relatively little and inexpensive maintenance. In hot summer and cold winter zones, employing low emissivity (low-e) glazing is preferable to meet the energy efficiency requirements [38]. For most residential buildings, the HVAC systems and lighting systems consume high amounts of energy. Considering the low efficiency of existing HVAC systems, replacing more efficient equipment is a priority ECM. Lowing the lighting power density (LPD) from artificial lights also considerably reduces energy consumption.

Table 3. Literature review of ECMs.

ECMs	Study							
	[29]	[37]	[38]	[39]	[40]	[41]	[42]	[43]
Insulating roof or wall	√	√	√	√	√	√	√	√
Replacing window	√	√	√	√	√	√	√	√
Replacing door	×	×	×	×	√	×	√	×
Using high-efficiency HVAC systems	√	√	√	√	√	×	√	√
Changing lighting system	×	√	√	√	√	×	√	×
Reducing air leakage	×	×	×	√	√	×	×	×
Using renewable energy	×	×	√	×	√	×	√	√
Utilizing energy-saving device	×	√	√	×	√	√	√	×
Lowering the heating set point temperature	×	×	×	√	×	×	√	×
Increasing the cooling set point temperature	×	×	×	√	×	×	×	×
Adding window shading	√	×	√	√	×	×	×	×

Therefore, seven kinds of ECMs are selected and their indicators are defined, referring to the Technical Standard for Nearly Zero Energy Buildings [44]; Graduations and Test Methods of Air Permeability, Water-tightness, Wind Load Resistance Performance for Building External Windows and Doors (GB/T 7106-2008) [45]; and the Standard for Lighting Design of Buildings (GB 50034-2013) [46], as summarized in Table 4.

Table 4. Commonly used retrofit indicators.

Scenario	Construction	Indicator	Limit Values in Standards
1	Exterior wall	U-value (W/(m^2·K))	≤0.6
2	Roof	U-value (W/(m^2·K))	≤0.4
3	window	U-value (W/(m^2·K))	≤2.0
		SHGC	≤0.3
4	Shading	Overhang depth (m)	-
5	Air sealing	Flow per exterior surface area (m^3/(m^2·s))	≤4.2 × 10^{-4}
6	Light	LPD (W/m^2))	≤5.0
7	Air condition	Cooling COP	3.20
		Heating COP	2.40

Table 4 lists the seven ECMs selected in this paper and their limited values, namely, adding EPS material layer on the outer wall and roof, replacing the original ordinary window with a low-e window, adding window shading facilities, adding PVC sealing strip to improve the air tightness of the building, and replacing the original air conditioning with a more efficient air conditioning system.

2.4. Retrofit Model Establishment

In this study, we have deepened the retrofit function of AutoBPS. When completing the establishment of the baseline models and the determination of ECMs, the retrofit models were generated by applying different ECMs to the baseline models. After selecting the retrofit structure, AutoBPS-Retrofit can automatically and rapidly model and generate corresponding energy consumption reports by simply inputting relevant parameters. The ways to achieve energy-saving retrofit using AutoBPS-Retrofit can be summarized as adding and modifying. The renovation of exterior walls and roofs requires adding EPS material to the EnergyPlus model and adding it to the outermost layer of the original walls or roofs. To achieve this step, the only parameter that users need to input is the thickness of EPS. For windows, new window structures need to be added and then applied to the exterior surface of the building. To achieve this step, the parameter that users need to input is the U value and SHGC of the new window system. For external shading, vertical overhangs will be added above the windows facing south by inputting the overhang depth. As for air sealing, lighting, and AC, the retrofit just needs to modify the original setting parameters in the EnergyPlus model. The parameters that need to be input for different ECMs are shown in Table 5. Upon user selection of an ECM and the input of the corresponding data, AutoBPS-Retrofit seamlessly processes this information to trigger automated modifications to the baseline models. This adjustment is achieved through code implementation, which effectively alters the underlying EnergyPlus model. For instance, considering the retrofit of exterior walls, AutoBPS-Retrofit generates a novel EPS board in the “Material” of EnergyPlus, mirroring the user-specified thickness. Subsequently, this newly created EPS board is integrated into the outermost layer of the original exterior wall in EnergyPlus’ “Construction” segment. As a result of these operations, retrofit models for exterior walls, distinct from the baseline models, are systematically generated.

Table 5. Input parameters for different ECMs.

Construction	Input Parameters
Exterior wall	EPS thickness
Roof	EPS thickness
Window	U value, SHGC
Shading	Overhang depth
Air sealing	Flow per exterior surface area
Light	LPD
Air condition	Cooling COP, heating COP

When carrying out retrofit, the limited range in standards and the materials available in reality should be considered simultaneously. The limited range has been given in Table 4. The material information, such as the actual market value of price and specification, can be acquired from www.gldjc.com. The attribute that the materials must have is calculated based on the minimum limit value, and then, the materials that meet the requirements can be found on the website. For the specifications, technical parameters, and unit prices of the materials used in these seven ECMs, see Table 6.

Table 6. Settings of models and material information.

Construction	Material Information						
	Year built	Indicator	Settings		Measure	Specification	Material price
			Baseline	Retrofit			
Exterior wall	Pre-2001 2001–2010 2010 and After	W/(m^2·K)	1.96 1 0.8	0.36 0.39 0.39	Adding EPS layers	80 mm 60 mm 50 mm	42.07 CNY/m^2 34.15 CNY/m^2 30.19 CNY/m^2
Roof	Pre-2001 2001–2010 2010 and After	W/(m^2·K)	1.66 0.8 0.5	0.29 0.34 0.34	Adding EPS layers	90 mm 65 mm 35 mm	46.03 CNY/m^2 36.13 CNY/m^2 24.25 CNY/m^2
Window	Pre-2001 2001–2010 2010 and After	W/(m^2·K)	6.6 3.2 2.8	1.60	Replacing existing windows with low-e glazing	5+12Ar+ 5Low-e+ 12Ar+5low-e	139 CNY/m^2
	Pre-2001 2001–2010 2010 and After	SHGC	0.85 0.48 0.34	0.287			
External shading	Pre-2001 2001–2010 2010 and After	m	0	0.75	Adding 90° overhang to windows facing south		504 CNY/m
Air sealing	Pre-2001 2001–2010 2010 and After	m^3/(m^2·s)	0.001	0.004	Adding PVC sealing strip		60 CNY/m
Light	Pre-2001 2001–2010 2010 and After	W/(m^2)	7 7 6	5	Replacing existing lights with LED		7.5 CNY/m^2
Air condition	Pre-2001 2001–2010 2010 and After	Cooling/ Heating COP	2.2/1 2.3/1.9 2.9/2.2	3.2/2.4	Replacing existing air condition with high-efficiency air condition		9000 CNY/h

Combined with the relative standards and [47,48] the settings of the baseline models, the determined values of every target construction after retrofit and the information on the materials used in this study are shown in Table 6.

2.5. Economic Analysis

Despite a higher environmental awareness in our society, costs are often the key factor for decision-making. In some places, retrofit cost-effectiveness has been called into question [49]. This increases the necessity for assessing the economic cases of retrofit projects. This study uses PBP and NPV to estimate the cost-effectiveness of all these ECMs. PBP calculates how many years the investment can be returned and compares the PBP with the remaining lifespan of target buildings to assess whether the ECM has a profitable effect. The equation is shown as follows:

$$PBP = \frac{C}{A}, \quad (1)$$

where C is the total cost of an ECM (CNY);

A is annual net saving (CNY).

The total cost, including the material, labor, and other expenses, can be calculated using Equation (2):

$$C = C_m + C_L + C_O, \quad (2)$$

where C_m is the cost of materials (CNY);

C_L is the labor cost (CNY);

C_O represents the other costs (CNY).

The cost information and calculation of total construction cost are seldom published, but the proportion of labor cost and material cost in the overall construction cost is quite consistent. Therefore, a method based on the consistent proportion is proposed. The ratio between the labor cost and material cost in mainland Chinese cities is 20% and 60%, respectively [38]. The relationship between labor and material cost and the overall cost is shown in Equations (3) and (4):

$$\frac{C_L}{C} = P_L, \tag{3}$$

(P_L is basically a constant, and it is assumed as 20% in the mainland.)

$$\frac{C_{ij}^{M^x}}{C_{ij}^{O^x}} = P_M, \tag{4}$$

(P_M is basically a constant, and it is assumed as 60% in this study.)

The annual net saving has a close relationship with local electricity prices. Changsha implements a tiered electricity pricing policy, but the equivalent electricity price P_e is calculated at 0.633 CNY/kWh for convenience. The annual net saving (A) can be calculated as Equation (5):

$$A = \Delta E \times S_F \times P_e, \tag{5}$$

$$\Delta E = E_b - E_r, \tag{6}$$

where E_b and E_r are EUI of baseline models and retrofit models, and S_F means the floor area of each type of residential building, as shown in Table 1.

Only knowingthe PBP of the investment of ECMs is not sufficient enough. To make the economic analysis more convincing, NPV should also be calculated as an indicator. NPV is a good indicator for judging whether the ECM is profitable. NPV can be calculated as Equation (7):

$$NPV = \sum_{t=1}^{N} \frac{A}{(1+i)^t} - C, \tag{7}$$

where i is the discount rate (i = 3%) [41,50,51], t denotes the analysis period in years, and N represents the remaining lifespan of target buildings.

If NPV is greater than 0, it can be considered that the investment has exceeded the expected level. An NPV less than 0 indicates that the expected return level has yet to be achieved, and it cannot be determined that the project has incurred losses. NPV is equal to 0, indicating that the investment return rate after project implementation is exactly as expected.

3. Results

In this section, we assess the impact of the seven ECMs from two perspectives: energy-saving effectiveness and cost-effectiveness. The energy-saving analysis involves a comparison of the energy consumption reports generated using AutoBPS-Retrofit before and after the retrofit. For the economic analysis, we evaluate the total cost of implementing the ECMs and the energy costs saved over the remaining lifespan of the retrofitted buildings.

With the improvement in environmental protection awareness, the Chinese government implements the control of energy use intensity (EUI) to prevent the excessive growth of energy usage [52]. EUI is an indicator of the energy efficiency of a building's design or operations and expresses as energy per square meter or foot per year. Using AutoBPS-Retrofit to simulate the baseline and retrofit models will automatically produce the energy consumption reports, including the information on EUI. After applying different ECMs, the EUI and energy-saving potential (ESP) of retrofit models are shown in Table 6. ESP can be calculated by comparing the EUI of baseline models and retrofit models, as Equation (8) shows:

$$ESP = \frac{\Delta E}{E_b} \times 100\% \quad (8)$$

Evaluating the economy of an ECM using PBP and NPV as an indicator depends on the total investment, total energy reduction in a life cycle, and the cost of energy. In China, the life span of residential buildings is usually 50 years. In this study, applying ECMs to buildings will not extend their life span. The remaining life span of residential buildings built before 2001, 2001–2010, and built after 2010 is assumed to be 20 years, 30 years, and 40 years.

3.1. Baseline Models of Residential Buildings in Changsha

The prototype models used in this study are from the United States Department of Energy. The baseline models are generated by modifying the prototype models based on the actual differences between the local area and the United States. Compared with the DOE prototype models, the EUI of baseline models is at a lower lever, which is more suitable for domestic situations, as shown in Figure 2.

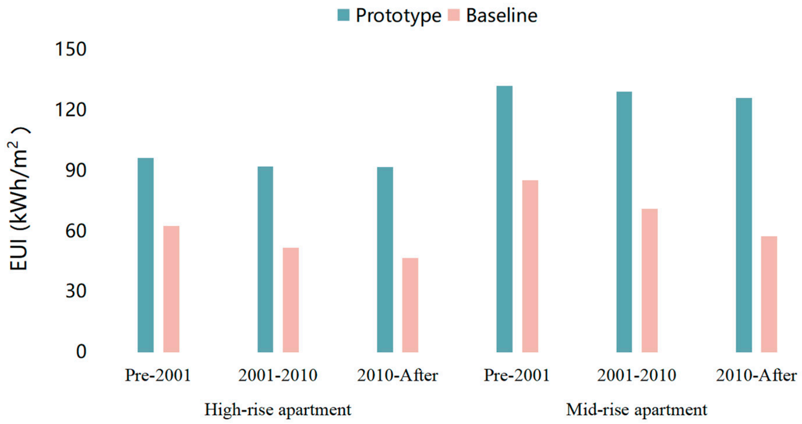

Figure 2. The EUI of prototype models and baseline models.

However, the EUI of the baseline model is still higher than the values from other studies. In hot summer and cold winter areas, the annual EUI in large-scale residential buildings ranges from 49 to 60 kWh/m^2. A significant mismatch between predicted energy performance and actual energy consumption of a building is frequently revealed. This is often referred to as the 'performance gap' [53,54]. These gaps are related not only to modeling errors but also to the behavior of residents, differences in real and simulated weather data, and equipment control strategies. Figure 3 shows the EUI of the baseline models.

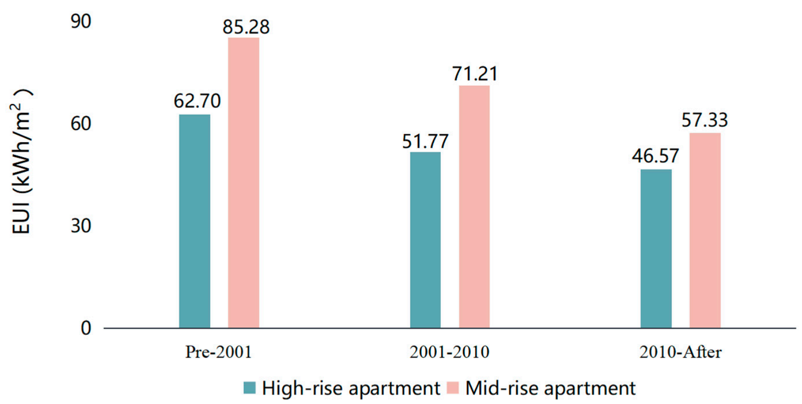

Figure 3. EUI of the baseline models.

It is clear that the residential buildings built earlier have higher EUI because of their bad thermal performance and aging equipment. The EUI range of high-rise apartments is between 46 and 63 kWh/m^2, while the mid-rise apartment is between 57 and 86 kWh/m^2.

3.2. Building Envelope Retrofitting

The building envelope, which has the highest impact on heating and cooling loads, is one of the main targets in retrofit projects [55]. Still, it is controversial due to the difficulty of implementation and economic benefits. Table 7 presents the outcomes derived from the AutoBPS-Retrofit simulations for envelope retrofitting. Notably, certain instances reveal a peculiar pattern, where the payback period (PBP) is shorter than the remaining lifespan, while the net present value (NPV) registers as less than zero. This phenomenon finds its explication in the distinction between PBP and NPV, which arises from divergent evaluative perspectives. PBP signifies the temporal span necessary for recovering the initial investment via net income garnered from the project. Conversely, NPV encapsulates the net cash flow post-project implementation. A higher NPV signifies superior economic benefits. Moreover, instances have arisen wherein distinct economic benefits transpire among residential structures of identical vintage, subject to identical energy conservation measures (ECMs). This peculiarity is discernible due to the varied geometric configurations among buildings of the same vintage. Despite uniform envelope structures and indoor equipment, the distinct ratios of walls to floors, walls to roofs, and other geometric attributes wield an influence over energy intensity. This intricate interplay means that even uniform ECM adoption may yield dissimilar energy-saving outcomes and economic benefits.

Table 7. The simulation result of retrofitting envelopes.

Building Type	Year Built	Construction	Energy-Saving Analysis			Economic Analysis	
			EUI (kWh/m^2)	Energy-Savings (kWh/m^2)	ESP (%)	PBP (Year)	NPV (Billion CNY)
High-rise apartments	Pre–2001	Exterior wall	61.19	1.51	2.41	25	−0.17
		Roof	61.85	0.85	1.36	15	−0.005
		Window	53.53	9.17	14.63	7	0.83
		Shading	59.43	3.27	5.21	23	−0.29
		Air sealing	61.50	1.19	1.91	45	−0.39
	2001–2010	Exterior wall	51.51	0.26	0.51	145	−0.73
		Roof	51.44	0.34	0.65	21	−0.001
		Window	50.44	1.33	2.58	32	−0.36
		Shading	48.45	3.33	6.43	19	0.003
		Air sealing	51.09	0.69	1.33	66	−0.70
	2010 and After	Exterior wall	42.41	4.16	8.94	9	2.06
		Roof	42.45	4.12	8.84	1	3.25
		Window	42.73	0.13	8.26	242	−1.01
		Shading	39.93	6.64	14.27	9	3.20
		Air sealing	42.40	4.17	8.96	11	1.83
Mid-rise apartments	Pre–2001	Exterior wall	77.99	7.29	8.54	5	1.28
		Roof	82.52	2.76	3.24	8	3.30
		Window	73.81	11.47	13.45	3	2.59
		Shading	78.09	7.19	8.43	12	0.39
		Air sealing	84.79	0.49	0.57	125	−0.99
	2001–2010	Exterior wall	60.23	10.98	15.42	4	2.53
		Roof	68.81	2.41	3.38	7	0.43
		Window	68.78	2.43	3.41	11	0.28
		Shading	66.49	4.73	6.64	19	0.007
		Air sealing	70.59	0.62	0.87	100	−0.72
	2010 and After	Exterior wall	54.23	3.10	5.41	12	0.32
		Roof	56.70	0.63	1.11	18	0.003
		Window	57.31	0.02	0.04	1364	−0.26
		Shading	54.26	3.07	5.36	27	−0.12
		Air sealing	57.31	0.02	0.04	2632	−0.57

And, the ESP and NPV of five kinds of envelopes for six kinds of residential buildings are displayed in Figure 4. The horizontal boundary represents NPV = 0, green areas represent NPV > 0, and pink areas represent NPV < 0.

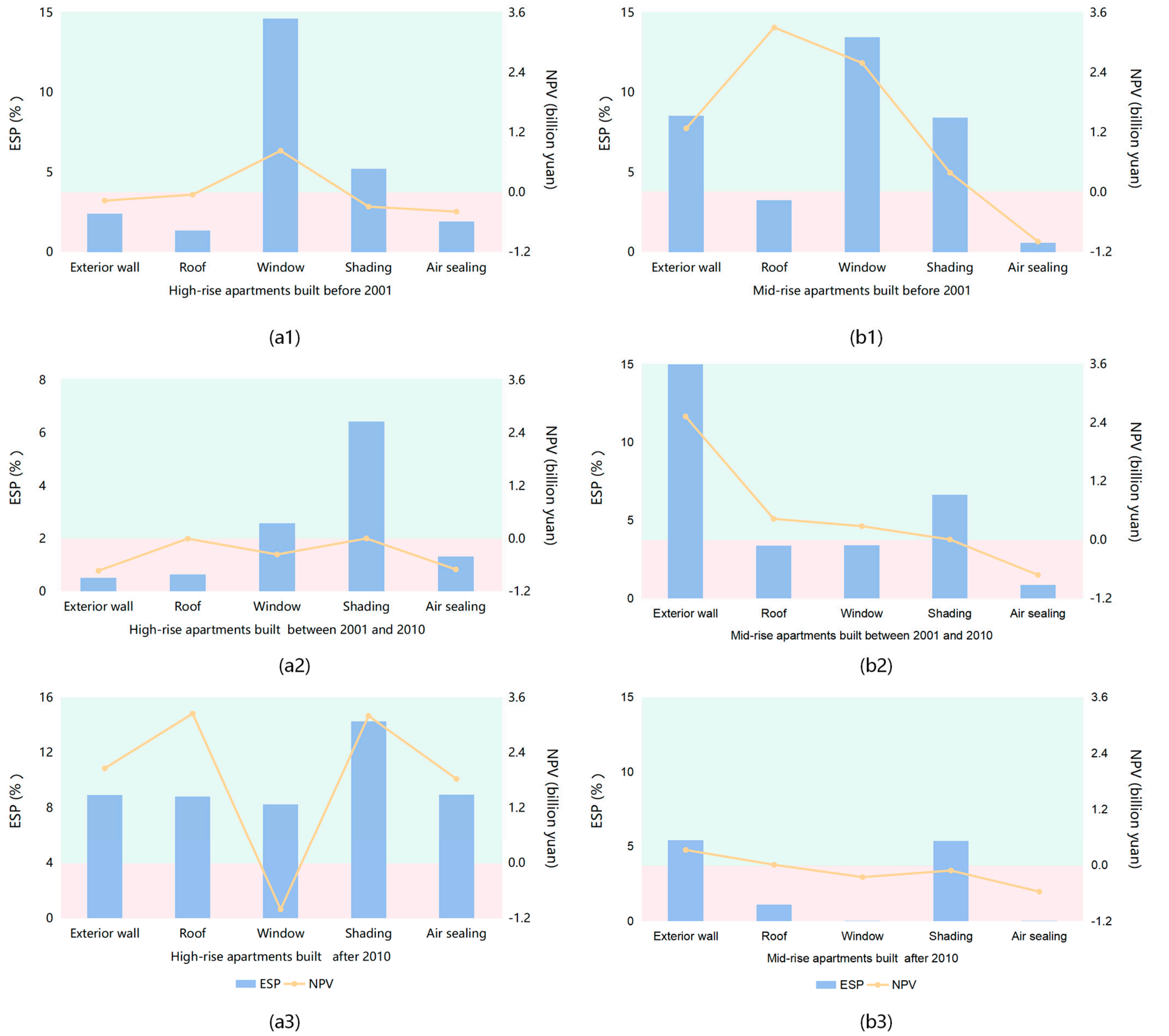

Figure 4. The ESP and NPV of five envelopes for six kinds of residential buildings: (**a1**–**a3**) high-rise apartments; (**b1**–**b3**) mid-rise apartments. Note: ESP means energy-saving percentage (%).

The envelope structures of three types of high-rise apartments have different characteristics before and after renovation, as seen in Figure 4. Firstly, for high-rise apartments built before 2001, replacing existing windows with low-e glass not only saves 15% of energy consumption but also has positive economic benefits, with a payback period of 7 years. Adding insulation panels to walls and roofs can save 2.4% and 1.4%, respectively, in energy consumption, adding external shading equipment can save 5.2%, and adding sealing strips can save 2.0%, but their NPV is all negative. Then, for high-rise apartments built between 2001 and 2010, adding external shading equipment is economically feasible while saving 6% of energy consumption, with a payback period of 19 years. The energy-saving effect of insulating exterior walls and roofs is insignificant, with ESPs of 0.5% and 0.7%, respectively. Improving the thermal performance of windows can save 2.6% of energy consumption, and installing sealing strips can save 1.3% of energy consumption, but they are not economical. Thirdly, for high-rise apartments built after 2010, adding insulation panels to the exterior walls and roofs, adding external shading equipment, and installing sealing strips are all economical ECMs. Their ESPs are 8.9%, 8.8%, 14.3%, and 9.0%, respectively, with a minimum payback period of 1 year and a maximum of 11 years. At the same time, although replacing windows can save 8.3% of energy consumption, its negative NPV indicates that it is not a priority.

The envelope structures of three types of mid-rise apartments also have different characteristics before and after renovation, as seen in Figure 4. Firstly, for mid-rise apartments built before 2001, insulating the exterior walls and roofs, replacing windows with better thermal performance, and installing external shading equipment are all economical ECMs, which can save energy by 8.5%, 3.2%, 13.5%, and 8.4%, respectively, with a payback period of 3–12 years. Installing the sealing strip can only save 0.6% of energy consumption, and its NPV is less than 0. Residential buildings constructed earlier in the hot summer and cold winter (HSCW) climate zone often overlooked energy-saving considerations, leading to subpar thermal performance. Consequently, enhancing the building envelopes yields notably positive outcomes. However, the scope for replacing sealing strips is limited in size, resulting in energy-saving effects that, while present, may not be as pronounced as other ECMs. Then, for mid-rise apartments built between 2001 and 2010, insulating exterior walls and roofs, replacing windows, and installing external shading equipment is cost-effective while providing significant energy savings. Their ESP is 15.4%, 3.4%, 3.4%, and 6.6%, respectively, with a payback period of 4–19 years. Installing sealing strips saves only 0.6% of energy consumption and is considered uneconomical. Thirdly, for mid-rise apartments built after 2010, insulating exterior walls and roofs are economic ECMs with ESP of 5.4% and 1.1%, respectively, and their payback periods are 12 and 18 years. Replacing windows and installing sealing strips have almost no energy-saving effects. Adding external shading equipment can save 5.4% of energy consumption, but their NPVs are all less than 0.

3.3. Lighting System Retrofitting

Substituting the lighting system with energy-efficient LEDs featuring a reduced LPD proves advantageous in terms of energy savings and economic gains across various residential building types examined in this study. This approach offers favorable outcomes due to its combination of minimal initial investment and substantial energy-saving potential. The results simulated using AutoBPS-Retrofit of retrofitting lighting systems are shown in Table 8. For high-rise apartments built before 2001, between 2001 and 2010, and after 2010, the ESPs are 6.0%, 7.7%, and 11.8%, respectively, with payback periods of 5 years, 5 years, and 4 years. For mid-rise apartments built before 2001, between 2001 and 2010, and after 2010, the ESPs are 5.4%, 13.6%, and 3.0%, respectively, with payback periods of 4 years, 2 years, and 12 years.

Table 8. The simulation result of retrofitting lighting systems.

Case	Construction	Energy-Saving Analysis			Economic Analysis	
		EUI (kWh/m^2)	Energy-Savings (kWh/m^2)	ESP (%)	PBP (Year)	NPV (Billion CNY)
1	Light	58.97	3.73	5.95	5	0.40
2		47.79	3.98	7.69	5	1.28
3		41.06	5.51	11.84	4	3.83
4		80.65	4.63	5.43	4	0.90
5		61.55	9.66	13.57	2	2.42
6		55.64	1.69	2.95	12	0.18

3.4. AC System Retrofitting

Generally, energy consumption by AC systems (heating and cooling) takes a dominant position in total building energy consumption. Therefore, we particularly emphasize the simulation of AC retrofitting. The energy consumption of AC was 50–70% for residential buildings [55]. The result simulated using AutoBPS-Retrofit shows that the HVAC system consumes 44% to 69% of the total energy consumption in residential buildings, while the lighting system consumes 16% to 26%. The results simulated using AutoBPS-Retrofit of retrofitting AC systems are shown in Table 9. In the context of residential buildings, enhancing the existing air conditioning system, while capable of substantially curtailing overall energy consumption, remains economically inadvisable. The substantial investment required for such an upgrade, attributed to elevated material and labor costs, renders it less favorable. Despite an impressive energy-savings potential, as indicated by an ESP of up to 18% for AC replacement, both the PBP and NPV metrics are persistently negative, underscoring the economic limitations of this approach.

Table 9. The simulation result of retrofitting AC.

Case	Construction	Energy-Saving Analysis			Economic Analysis	
		EUI (kWh/m^2)	Energy-Savings (kWh/m^2)	ESP (%)	PBP (Year)	NPV (Billion CNY)
1	AC	51.41	11.29	18.00	26	−1.33
2		45.42	6.35	12.27	39	−2.67
3		40.99	5.58	11.97	43	−3.97
4		76.10	9.18	10.76	36	−3.53
5		64.89	6.32	8.87	53	−3.00
6		55.83	1.50	2.61	215	−2.70

In addition, we also simulated the impact of two ways of changing human behavior on energy consumption. The first is to slightly change the AC setting temperature, and the second is for residents to consciously reduce the AC usage time. The simulation results show that artificially reducing the set temperature of the air conditioner by 1 degree can save 1% to 8% of energy consumption, and using natural ventilation without air conditioning at night can save up to 20% of energy consumption.

4. Discussion

Geared towards expediting retrofit analysis for city-scale buildings, this paper extends the development of energy-saving retrofit functions based on the prior study. Focusing on the existing mid-rise and high-rise apartments in Changsha, we propose seven distinct ECMs, seamlessly integrating them into baseline models derived from the modification of DOE prototype models to align with local standards.

By comparing baseline and retrofit models, ESP serves as an indicator to evaluate energy-saving effects, while PBP and NPV gauge economic benefits. The results underscore the necessity of tailoring retrofit strategies, a critical consideration when addressing envelope enhancements, as these strategies need to be finely tuned according to building types and built vintage. Notably, retrofits targeting lighting systems demonstrate both promising energy savings and favorable economic viability, albeit subject to residents' preferences. Alternatively, upgrading the AC systems emerges as the most energy-efficient approach, though the economic assessment raises concerns.

In the economic analysis of building energy efficiency renovations, consistent with the studies of Gonzalez-Caceres [56], Dodoo [57], Husiev [58], and Fleur [59], local fixed electricity prices were adopted. However, considering future electricity price prediction methods such as the GARCH model [60], transfer learning [61], and long short-term memory network [62] could yield dynamic electricity prices over time, enhancing the precision of PBP and NPV calculations [63], a direction we aim to explore.

Echoing previous research [64], this study reveals that the efficacy of specific ECMs and their economic impact depend on the building type and built vintage, sometimes yielding less effective outcomes and negative economic returns, as shown in Figure 5. Distinguishing this study is its emphasis on the economic analysis of energy-saving retrofits. For large-scale buildings, AutoBPS-Retrofit boasts swift computation and cross-platform simulation advantages.

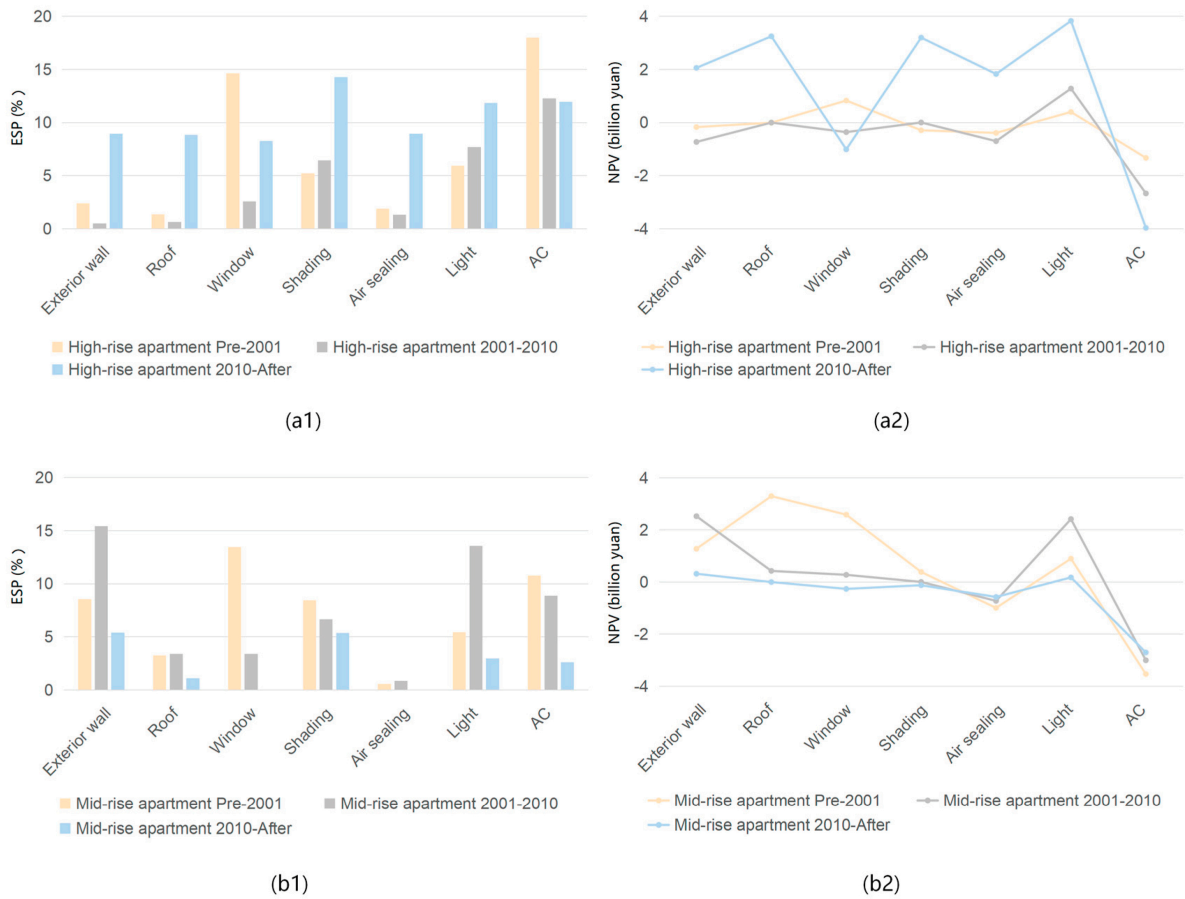

Figure 5. The ESP and NPV of the same ECMs to different kinds of residential buildings: (**a1**,**a2**) high-rise apartments (**b1**,**b2**) mid-rise apartments.

Nevertheless, the simulated EUI of baseline models is still higher than the actual EUI obtained through literature research. To enhance the practicality of baseline models, forthcoming steps involve an on-site investigation. Employing questionnaire surveys and empirical measurements, we aim to glean deeper insights into building characteristics, including window-wall ratio, room types, and air conditioning schedules, to refine baseline models with more granular parameters and classifications, thereby minimizing performance disparities.

Furthermore, this study solely examines scenarios where a single ECM is applied to a building. Subsequent phases will explore the combination of multiple ECMs to ascertain the most efficient and economical synergy, accounting for their potential interactions. Different building functions warrant diverse energy-saving criteria, necessitating the expansion of ECM types, such as optimizing automatic control systems for commercial buildings.

The ongoing pursuit entails automating energy-saving and economic analysis. This step necessitates a material database to empower users with options, collecting and organizing data on thermal performance, energy efficiency ratios, prices, and other factors associated with materials and equipment used in each structure. Expanding this approach to various climate zone is also a crucial consideration.

5. Conclusions

This paper presents an applicable framework for retrofit analysis utilizing the innovative AutoBPS-Retrofit toolkit, comprising six major steps: data collection, building classification, baseline model establishment, ECMs identification, retrofit model establishment, and retrofit analysis. The simulation process explores seven kinds of ECMs encompassing envelope optimization, lighting system upgrades, and AC system control.

The findings of this study highlight the importance of tailored retrofit strategies for buildings of different types and ages when addressing envelope improvements. Additionally, retrofitting lighting systems showcases promising energy-saving potential with favorable economic viability. However, successfully implementing lighting retrofits hinges on residents' preferences and engagement. Conversely, upgrading the AC systems emerges as the most energy-efficient measure. Yet, it is imperative to acknowledge that the economic analysis raises concerns, revealing that the investment required for such upgrades considerably surpasses the expected returns based on both the payback period (PBP) and net present value (NPV) indicators.

The findings can offer valuable insights for policymakers in establishing effective carbon reduction goals and strategies. Additionally, various energy-saving institutions and real-estate companies can leverage this research as a valuable reference when undertaking renovation projects aimed at enhancing energy efficiency in residential buildings.

Author Contributions: Conceptualization, Y.J., Y.C. and R.Z.; Methodology, Y.J. and Y.C.; Software, Y.J. and Y.C.; Validation, G.L., F.S., Y.C. and R.Z.; Formal analysis, Y.J., G.L. and F.S.; Investigation, Y.J.; Data curation, Y.J.; Writing—original draft, Y.J., G.L. and F.S.; Writing—review & editing, Y.C. and R.Z.; Visualization, Y.J.; Supervision, Y.C.; Funding acquisition, Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Hunan University, China, through the start-up funds and the Course Development Program of "Artificial Intelligence in Built Environment".

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rohács, D. Analysis and Optimization of Potential Energy Sources for Residential Building Application. *Energy* **2023**, *275*, 127508. [CrossRef]
2. Economidou, M.; Todeschi, V.; Bertoldi, P.; D'Agostino, D.; Zangheri, P.; Castellazzi, L. Review of 50 years of EU Energy Efficiency Policies for Buildings. *Energy Build.* **2020**, *225*, 110322. [CrossRef]
3. Hu, J.; Kawaguchi, K.; Ma, J.; Nakaso, Y. Improving Indoor Thermal and Energy Performance of Large-Space Residential Buildings via Active Approaches. *Appl. Energy* **2023**, *344*, 120766. [CrossRef]
4. Ahady, S.; Dev, N.; Mandal, A. Sustainable Energy Retrofit Plan for Enhancing Energy Efficiency of Residential Apartments in Arid Climate: Case of Afghanistan. *Sādhanā* **2022**, *47*, 131. [CrossRef]
5. Peng, Z.; Zhao, S.; Shen, L.; Ma, Y.; Zhang, Q.; Deng, W. Retrofit or Rebuild? The Future of Old Residential Buildings in Urban Areas of China Based on the Analysis of Environmental Benefits. *Int. J. Low-Carbon Technol.* **2021**, *16*, 1422–1434. [CrossRef]
6. La Fleur, L.; Rohdin, P.; Moshfegh, B. Energy Renovation versus Demolition and Construction of a New Building—A Comparative Analysis of a Swedish Multi-Family Building. *Energies* **2019**, *12*, 2218. [CrossRef]
7. Gaspar, P.L.; Santos, A.L. Embodied Energy on Refurbishment vs. Demolition: A Southern Europe Case Study. *Energy Build.* **2015**, *87*, 386–394. [CrossRef]
8. Bao, L.; Zhao, J.; Zhu, N. Analysis and Proposal of Implementation Effects of Heat Metering and Energy Efficiency Retrofit of Existing Residential Buildings in Northern Heating Areas of China in "the 11th Five-Year Plan" Period. *Energy Policy* **2012**, *45*, 521–528. [CrossRef]
9. Biekša, D.; Šiupšinskas, G.; Martinaitis, V.; Jaraminienė, E. Energy Efficiency Challenges in Muti-Apartment Building Renovation in Lithuania. *J. Civ. Eng. Manag.* **2011**, *17*, 467–475. [CrossRef]
10. Jia, L.; Qian, Q.K.; Meijer, F.; Visscher, H. Exploring Key Risks of Energy Retrofit of Residential Buildings in China with Transaction Cost Considerations. *J. Clean. Prod.* **2021**, *293*, 126099. [CrossRef]

11. Liu, C.; Mohammadpourkarbasi, H.; Sharples, S. Evaluating the Potential Energy Savings of Retrofitting Low-Rise Suburban Dwellings towards the Passivhaus EnerPHit Standard in a Hot Summer/Cold Winter Region of China. *Energy Build.* **2021**, *231*, 110555. [CrossRef]
12. Fu, X.; Qian, X.; Wang, L. Energy Efficiency for Airtightness and Exterior Wall Insulation of Passive Houses in Hot Summer and Cold Winter Zone of China. *Sustainability* **2017**, *9*, 1097. [CrossRef]
13. Liu, C.; Ma, W.; Hao, J.; Luo, D.; Zuo, J.; Zhang, C. Energy Retrofitting Assessment of Public Building Envelopes in China's Hot Summer and Cold Winter Climate Region. *Buildings* **2022**, *12*, 1866. [CrossRef]
14. Wang, P.; Ji, C.; Yu, P.; Huang, L. A Procedure Set to Construct the Optimal Energy Saving Retrofit Strategy for Old Residential Buildings in China. *J. Renew. Sustain. Energy* **2023**, *15*, 025101. [CrossRef]
15. Ma, Z.; Cooper, P.; Daly, D.; Ledo, L. Existing Building Retrofits: Methodology and State-of-the-Art. *Energy Build.* **2012**, *55*, 889–902. [CrossRef]
16. Huang, H.; Binti Wan Mohd Nazi, W.I.; Yu, Y.; Wang, Y. Energy Performance of a High-Rise Residential Building Retrofitted to Passive Building Standard—A Case Study. *Appl. Therm. Eng.* **2020**, *181*, 115902. [CrossRef]
17. Short, C.A.; Song, J.; Mottet, L.; Chen, S.; Wu, J.; Ge, J. Challenges in the Low-Carbon Adaptation of China's Apartment Towers. *Build. Res. Inf.* **2018**, *46*, 899–930. [CrossRef]
18. Yao, R.; Costanzo, V.; Li, X.; Zhang, Q.; Li, B. The Effect of Passive Measures on Thermal Comfort and Energy Conservation. A Case Study of the Hot Summer and Cold Winter Climate in the Yangtze River Region. *J. Build. Eng.* **2018**, *15*, 298–310. [CrossRef]
19. Qu, K.; Chen, X.; Wang, Y.; Calautit, J.; Riffat, S.; Cui, X. Comprehensive Energy, Economic and Thermal Comfort Assessments for the Passive Energy Retrofit of Historical Buildings—A Case Study of a Late Nineteenth-Century Victorian House Renovation in the UK. *Energy* **2021**, *220*, 119646. [CrossRef]
20. Huang, H.; Wang, H.; Hu, Y.-J.; Li, C.; Wang, X. Optimal Plan for Energy Conservation and CO2 Emissions Reduction of Public Buildings Considering Users' Behavior: Case of China. *Energy* **2022**, *261*, 125037. [CrossRef]
21. Li, Q.; Zhang, L.; Zhang, L.; Wu, X. Optimizing Energy Efficiency and Thermal Comfort in Building Green Retrofit. *Energy* **2021**, *237*, 121509. [CrossRef]
22. Lupisek, A.; Sojková, K.; Volf, M.; Hejtmánek, P. Potential for Energy Savings in Czech Residential Building Stock by Application of a Prefabricated Mass Retrofitting System. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Graz, Austria, 11–14 September 2019; Institute of Physics Publishing: London, UK, 2019; Volume 323.
23. Yang, X.; Liu, S.; Zou, Y.; Ji, W.; Zhang, Q.; Ahmed, A.; Han, X.; Shen, Y.; Zhang, S. Energy-Saving Potential Prediction Models for Large-Scale Building: A State-of-the-Art Review. *Renew. Sustain. Energy Rev.* **2022**, *156*, 111992. [CrossRef]
24. Teso, L.; Carnieletto, L.; Sun, K.; Zhang, W.; Gasparella, A.; Romagnoni, P.; Zarrella, A.; Hong, T. Large Scale Energy Analysis and Renovation Strategies for Social Housing in the Historic City of Venice. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102041. [CrossRef]
25. Deng, Z.; Chen, Y.; Yang, J.; Causone, F. AutoBPS: A Tool for Urban Building Energy Modeling to Support Energy Efficiency Improvement at City-Scale. *Energy Build.* **2023**, *282*, 112794. [CrossRef]
26. Adilkhanova, I.; Santamouris, M.; Yun, G.Y. Coupling Urban Climate Modeling and City-Scale Building Energy Simulations with the Statistical Analysis: Climate and Energy Implications of High Albedo Materials in Seoul. *Energy Build.* **2023**, *290*, 113092. [CrossRef]
27. Afshari, A. Optimization of Urban Design/Retrofit Scenarios Using a Computationally Light Standalone Urban Energy/Climate Model (SUECM) Forced by ERA5 Data. *Energy Build.* **2023**, *287*, 112991. [CrossRef]
28. Mousavi, S.; Gheibi, M.; Wacławek, S.; Behzadian, K. A Novel Smart Framework for Optimal Design of Green Roofs in Buildings Conforming with Energy Conservation and Thermal Comfort. *Energy Build.* **2023**, *291*, 113111. [CrossRef]
29. Tsang, C.; Spentzou, E.; Lomas, K.J.; He, M. Reducing Energy Consumption and Improving Comfort by Retrofitting Residential Buildings in the Hot Summer and Cold Winter Zone of China. *J. Archit. Eng.* **2022**, *28*. [CrossRef]
30. Ma, R.; Fang, D.; Chen, J.; Li, X. A Tiled Multi-City Urban Objects Dataset for City-Scale Building Energy Simulation. *Sci. Data* **2023**, *10*, 352. [CrossRef]
31. Li, Y.; Wang, C.; Zhu, S.; Yang, J.; Wei, S.; Zhang, X.; Shi, X. A Comparison of Various Bottom-up Urban Energy Simulation Methods Using a Case Study in Hangzhou, China. *Energies* **2020**, *13*, 4781. [CrossRef]
32. *GB50352-2019*; Uniform Standard for Design of Civil Buildings. China Building Industry Press: Beijing, China, 2019.
33. Deng, Z.; Chen, Y.; Yang, J.; Chen, Z. Archetype Identification and Urban Building Energy Modeling for City-Scale Buildings Based on GIS Datasets. *Build. Simul.* **2022**, *15*, 1547–1559. [CrossRef]
34. *JGJ134-2001*; Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone. China Building Industry Press: Beijing, China, 2001.
35. *JGJ134-2010*; Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone. China Building Industry Press: Beijing, China, 2010.
36. He, C. Study on Energy Consumption Optimization Mechanism and Strategy of Passive Residential Building in Hot Summer and Cold Winter Area. Master's Thesis, Jiangsu University of Science and Technology, Zhenjiang, China, 2022.

37. Qian, D.; Li, Y.; Niu, F.; O'Neill, Z. Nationwide Savings Analysis of Energy Conservation Measures in Buildings. *Energy Convers. Manag.* **2019**, *188*, 1–18. [CrossRef]
38. He, Q.; Hossain, M.U.; Ng, S.T.; Augenbroe, G. Identifying Practical Sustainable Retrofit Measures for Existing High-Rise Residential Buildings in Various Climate Zones through an Integrated Energy-Cost Model. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111578. [CrossRef]
39. Monna, S.; Juaidi, A.; Abdallah, R.; Salameh, T. Sustainable Energy Retrofitting for Residential Buildings in Palestine, a Simulation Based Approach. In Proceedings of the 2021 12th International Renewable Engineering Conference, IREC 2021, Amman, Jordan, 14–15 April 2021; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2021.
40. Rabani, M.; Madessa, H.B.; Nord, N. A State-of-Art Review of Retrofit Interventions in Buildings towards Nearly Zero Energy Level. *Energy Procedia* **2017**, *134*, 317–326. [CrossRef]
41. Chen, S.; Guan, J.; Levine, M.D.; Xie, L.; Yowargana, P. Elaboration of Energy Saving Renovation Measures for Urban Existing Residential Buildings in North China Based on Simulation and Site Investigations. *Build. Simul.* **2013**, *6*, 113–125. [CrossRef]
42. Liu, L.; Moshfegh, B.; Akander, J.; Cehlin, M. Comprehensive Investigation on Energy Retrofits in Eleven Multi-Family Buildings in Sweden. *Energy Build.* **2014**, *84*, 704–715. [CrossRef]
43. Niemelä, T.; Kosonen, R.; Jokisalo, J. Cost-Effectiveness of Energy Performance Renovation Measures in Finnish Brick Apartment Buildings. *Energy Build.* **2017**, *137*, 60–75. [CrossRef]
44. *GB/T51350-2019*; Technical Standard for Nearly Zero Energy Buildings. China Building Industry Press: Beijing, China, 2019.
45. *GB/T 7106-2008*; Graduations and Test Methods of Air Permeability, Water-tightness, Wind Load Resistance Performance for Building External Windows and Doors. Standards Press of China: Beijing, China, 2008.
46. *GB 50034-2013*; Standard for Lighting Design of Buildings. China Building Industry Press: Beijing, China, 2014.
47. Liu, H.; Wu, Y.; Li, B.; Cheng, Y.; Yao, R. Seasonal Variation of Thermal Sensations in Residential Buildings in the Hot Summer and Cold Winter Zone of China. *Energy Build.* **2017**, *140*, 9–18. [CrossRef]
48. Weerasuriya, A.U.; Zhang, X.; Gan, V.J.L.; Tan, Y. A Holistic Framework to Utilize Natural Ventilation to Optimize Energy Performance of Residential High-Rise Buildings. *Build Environ.* **2019**, *153*, 218–232. [CrossRef]
49. Liu, Y.; Liu, T.; Ye, S.; Liu, Y. Cost-Benefit Analysis for Energy Efficiency Retrofit of Existing Buildings: A Case Study in China. *J. Clean. Prod.* **2018**, *177*, 493–506. [CrossRef]
50. Wang, H. Research on Energy-Saving Reconstruction of Existing Residential Buildings in Towns in Qingdao. Master's Thesis, Qingdao University of Technology, Qingdao, China, 2021.
51. He, Q.; Ng, S.T.; Hossain, M.U.; Augenbroe, G. Sustainable Building Retrofit Model for Highrise, High-Density City: A Case in Hong Kong. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2020**, *174*, 69–82. [CrossRef]
52. Cao, X.; Yao, R.; Ding, C.; Zhou, N.; Yu, W.; Yao, J.; Xiong, J.; Xu, Q.; Pan, L.; Li, B. Energy-Quota-Based Integrated Solutions for Heating and Cooling of Residential Buildings in the Hot Summer and Cold Winter Zone in China. *Energy Build.* **2021**, *236*, 110767. [CrossRef]
53. Menezes, A.C.; Cripps, A.; Bouchlaghem, D.; Buswell, R. Predicted vs. Actual Energy Performance of Non-Domestic Buildings: Using Post-Occupancy Evaluation Data to Reduce the Performance Gap. *Appl. Energy* **2012**, *97*, 355–364. [CrossRef]
54. de Wilde, P. The Gap between Predicted and Measured Energy Performance of Buildings: A Framework for Investigation. *Autom. Constr.* **2014**, *41*, 40–49. [CrossRef]
55. Xu, L.; Liu, J.; Pei, J.; Han, X. Building Energy Saving Potential in Hot Summer and Cold Winter (HSCW) Zone, China-Influence of Building Energy Efficiency Standards and Implications. *Energy Policy* **2013**, *57*, 253–262. [CrossRef]
56. Gonzalez-Caceres, A.; Karlshøj, J.; Arvid Vik, T.; Hempel, E.; Rammer Nielsen, T. Evaluation of Cost-Effective Measures for the Renovation of Existing Dwellings in the Framework of the Energy Certification System: A Case Study in Norway. *Energy Build.* **2022**, *264*, 112071. [CrossRef]
57. Dodoo, A.; Gustavsson, L.; Tettey, U.Y.A. Final Energy Savings and Cost-Effectiveness of Deep Energy Renovation of a Multi-Storey Residential Building. *Energy* **2017**, *135*, 563–576. [CrossRef]
58. Husiev, O.; Campos-Celador, A.; Álvarez-Sanz, M.; Terés-Zubiaga, J. Why District Renovation Is Not Leading the Race? Critical Assessment of Building Renovation Potential under Different Intervention Levels. *Energy Build.* **2023**, *295*, 113288. [CrossRef]
59. La Fleur, L.; Rohdin, P.; Moshfegh, B. Investigating Cost-Optimal Energy Renovation of a Multifamily Building in Sweden. *Energy Build.* **2019**, *203*, 109438. [CrossRef]
60. Kapoor, G.; Wichitaksorn, N. Electricity Price Forecasting in New Zealand: A Comparative Analysis of Statistical and Machine Learning Models with Feature Selection. *Appl. Energy* **2023**, *347*, 121446. [CrossRef]
61. Gunduz, S.; Ugurlu, U.; Oksuz, I. Transfer Learning for Electricity Price Forecasting. *Sustain. Energy Grids Netw.* **2023**, *34*, 100996. [CrossRef]
62. Meng, A.; Wang, P.; Zhai, G.; Zeng, C.; Chen, S.; Yang, X.; Yin, H. Electricity Price Forecasting with High Penetration of Renewable Energy Using Attention-Based LSTM Network Trained by Crisscross Optimization. *Energy* **2022**, *254*, 124212. [CrossRef]

63. Gremmelspacher, J.M.; Campamà Pizarro, R.; van Jaarsveld, M.; Davidsson, H.; Johansson, D. Historical Building Renovation and PV Optimisation towards NetZEB in Sweden. *Sol. Energy* **2021**, *223*, 248–260. [CrossRef]
64. Friedman, C.; Becker, N.; Erell, E. Energy Retrofit of Residential Building Envelopes in Israel: A Cost-Benefit Analysis. *Energy* **2014**, *77*, 183–193. [CrossRef]