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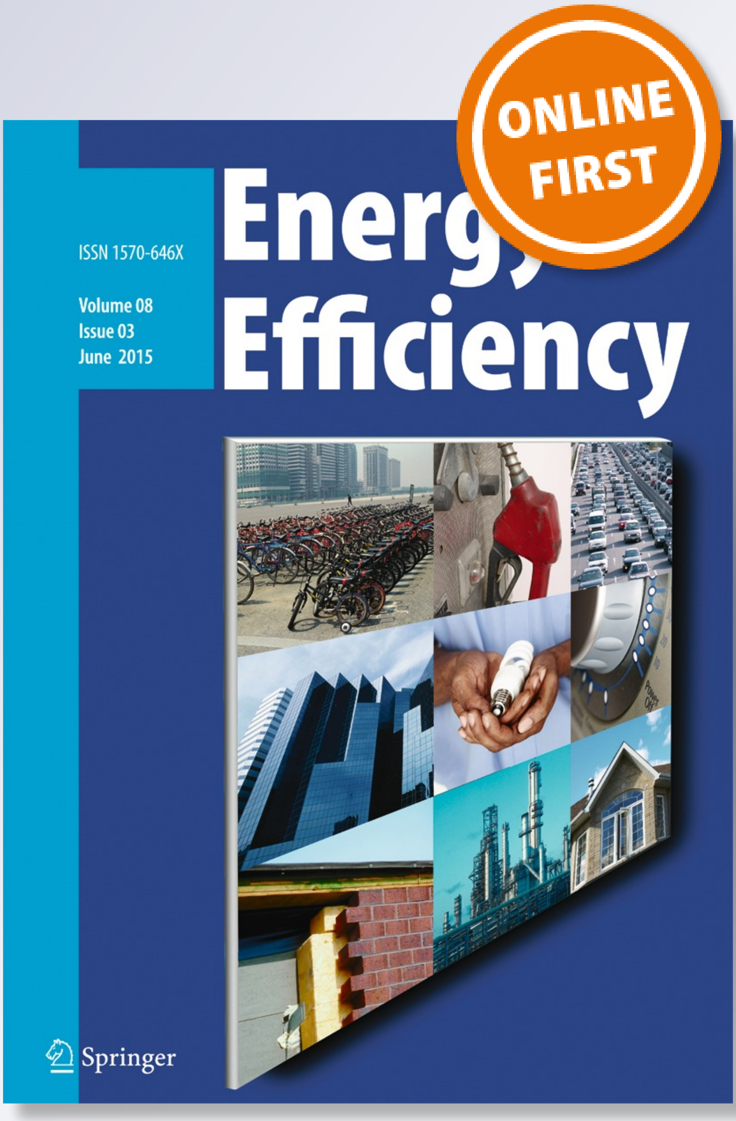

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ORIGINAL ARTICLE

Assessment of energy-saving technologies retrofitted to existing public buildings in China

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Eric Chang · Ying Ji**

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Abstract This study compared and analyzed both the energy savings and cost-effectiveness of various energy-saving technologies retrofitted to common buildings in China. Base models for an office and store building, set in representative climate zones of China—Beijing, Shanghai, and Guangzhou—were established and calibrated in EnergyPlus, a building energy simulation software program. Various energy-saving technologies were then applied to these models in EnergyPlus to calculate the overall energy savings under different climate conditions. In addition, a payback analysis was performed to determine the cost-effectiveness of each technology. The final results of this study can serve as a preliminary reference for selecting effective and economical energy-saving technologies to retrofit existing public buildings.

Keywords Commercial building · Energy simulation · Energy-saving retrofit · Economic assessment

Introduction

With China's continued high economic growth, energy consumption will only continue to rise, exerting tremendous pressure on the power supply (Jiang 2007). Thus, it is of vital importance that the country finds ways to improve energy efficiency and reduce energy waste, or risk the development of serious social problems and curbs to this growth (Fang 2007). Buildings have come into the spotlight as an area where significant energy savings can be achieved; existing buildings in particular present the largest potential. Retrofitting existing buildings has the potential to reduce energy usage by 30–40 % (Xu et al. 2012). Today, there are many energy-saving technologies available for use in retrofitting buildings, but the effectiveness of each method depends on a variety of factors including building types, local climates, occupant habits, HVAC system types, building enclosure properties, building geometries, etc. With results that differ so widely, there is no quick way for policymakers and engineers to decide on suitable energy-saving methods. In light of this issue, a number of studies have been carried out abroad and in China to analyze the effectiveness of retrofit methods in different buildings.

The European research group Ecofys for EURIMA conducted long-term research on the efficiency and economy of some common retrofit methods based on the unique climate features of different countries in Europe, and put forward the most appropriate energy-saving technologies for particular regions (Ecofys for EURIMA 2004, 2005). Griffith et al. from Lawrence Berkeley National Laboratory (LBNL) in the USA selected 4820 measured data points based on real experiments and through extensive computer simulations calculated the largest energy-saving potential of various technologies (Griffith et al. 2007). They concluded that US commercial buildings could achieve a 43 % energy

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savings over the code requirements of ASHRAE-90.1 (American Society of Heating, Refrigeration and Air-Conditioning Engineers) and also found that 65 % of buildings have the potential to become net-zero energy buildings. Based on the requirements of ASHRAE 90.1-2004, ASHRAE 90.1-2007, and Low Energy Case (LEC) design, Kneifel simulated some common retrofit methods in the USA applied to 12 buildings of different types in different climate zones and provided the simulation results (Kneifel 2010). In addition, Kneifel calculated the payback period and carbon emission reductions of common retrofit methods after using different buildings to compute life-cycles, and did some comparative analyses. In China, Li et al. modeled a typical office building and hotel building in Shanghai using EnergyPlus. They then simulated those models and compared the efficiencies of various energy-saving methods applied to those models (Li et al. 2008). However, further economic analyses of these methods were not carried out. Wu and Long established a model for a typical public building in Shanghai using DOE-2 and tested the effect of various enclosure retrofits and different HVAC operating schedules on building energy consumption (Wu and Long 2008).

Based on this survey of existing literature, the most comprehensive studies were found in the developed world while the research in China is so far still in its preliminary stage. There has yet to be a comprehensive survey of retrofit technologies applied to different buildings under varying climate zones in China. This study is an initial effort at solving this research problem. A primary concern in the field of energy efficiency is to use limited resources to create the maximum benefit and achieve the greatest reduction in energy consumption by applying the most suitable energy-saving technologies. The purpose of this paper was to establish building models in EnergyPlus with climate and building energy consumption data in China which were then used to analyze the energy savings and economic benefits of some typical retrofit methods. Having examined both the economic feasibility and energy savings of typical energy-saving methods, we have conducted a more comprehensive evaluation of these technologies, giving policymakers and engineers better information when selecting energy-saving strategies.

Methodology

We first needed to narrow down the field of possible retrofit methods into a manageable list. Common methods such as improving thermal insulation, using natural cooling/heating sources, increasing the efficiency of HVAC systems, and improving lighting conditions were selected. Next, we established a base model of prototypical public buildings in EnergyPlus to present different climate zones in China and calibrated its accuracy based on relevant standards and real data. Shanghai (hot summer and cold winter), Guangzhou (hot summer and warm winter), and Beijing (cold summer and winter) were selected as representative cities. In order to establish these building models, a calibrated simulation approach was taken, and energy consumption data was sourced from a wide range of studies. After calibration, we simulated these models with different retrofit methods applied and calculated their energy savings by comparing simulation results of the modified and original base building models. To analyze the cost-effectiveness of each method, we calculated their payback periods. With these results, a table summarizing the best and worst retrofit methods for each building type according to different climate zones in China was provided.

Energy-saving retrofit methods

Building energy consumption primarily consists of heating/cooling, lighting, equipment, and daily maintenance. Retrofit methods address these areas of concern, for example, by improving the thermal insulation of enclosures, increasing the efficiency of heating/cooling systems, and reducing energy use from lights (Ma et al. 2012). In this study, a total of 19 commonly used retrofit methods were studied (see Table 1).

Establishment and calibration of building models

Modeling approach

To study the effect of various retrofit methods, base models for the two building types (office and store building) in the three climate regions (Beijing,

Table 1 Classification of retrofit methods studied

Methods	Classification	Number	EEM lifetime	Method
Enclosure	A	A1	30	External wall 10 mm EPS[a]
		A2	30	External wall 20 mm EPS[a]
		A3	30	External wall 30 mm EPS[a]
		A4	30	Roof 30 mm XPS[a]
		A5	15	High-solar-gain low-E[b] (SC≥0.5)
		A6	15	Low-solar-gain low-E[b] (SC<0.5)
		A7	15	Window reflecting film[b]
		A8	20	Blind, external shading[c]
		A9	20	Roller shutter, external shading (translucent)[c]
		A10	20	Roller shutter, external shading (opaque)[c]
Cooling/heating source system	B	B1	30	Exhaust air heat recovery (standard fresh air)[d]
		B2	30	Exhaust air heat recovery (high fresh airflow rate)[d]
		B3	30	Fresh air free cooling[d]
		B4	30	Fresh air free cooling (extended cooling)[d]
		B5	30	Cooling tower cooling (direct)[d]
		B6	30	Cooling tower cooling (indirect)[d]
Distribution system	C	C1	15	VFD pumps[e]
Lighting system	D	D1	10	Energy-efficient lamps (LED)[f]
		D2	30	Daylighting[f]

[a] Exterior insulation materials: expanded polystyrene (EPS) and expandable polystyrene (XPS) are two kinds of thermal insulation material used in external walls and roofs, respectively, to reduce heat loss between the indoor and outdoor environments

[b] Windows: glass windows are a large source of heat gain during the summer and heat loss during the winter. Low-E glass reflects infrared rays decreasing surface radiation and reducing heat loss. Window reflecting film reduces solar transmittance without blocking infrared rays. High-solar-gain low-E window usually has a high SC (SC≥0.5), they do well in preventing the heat from escaping and is suitable for cold areas. Low-solar-gain low-E window has relatively lower SC (SC<0.5), which prevent outside heat from entering the room, and thus is suitable for warm or hot areas

[c] External Shading: movable louver shading (blinds) and movable roller shutter shadings are methods for reducing sunlight penetration

[d] HVAC System: exhaust air heat recovery reuses the energy from the heated/cooled exhaust air, reducing the need to heat or cool incoming fresh air. Fresh air free cooling is used when the outdoor enthalpy is lower than the indoor enthalpy to shorten chiller operating time and improve air quality. Cooling tower free cooling takes advantage of outdoor conditions to provide cooling, reducing the operating time of chillers

[e] Distribution system: variable frequency drives (VFDs) are used in pumps to reduce their energy consumption when the system does not require the maximum load

[f] Lighting system: Energy-efficient lamps (LED) reduce electricity consumption and daylighting uses natural sunlight to reduce the need for artificial lighting

Shanghai, and Guangzhou) need to be established first. In order to create these models, a calibrated simulation approach was taken. Using forward modeling, we first established a typical public building model using information about the building function and operating time, the HVAC system, the indoor loads, and the enclosure properties.

Next, the full-year energy consumption data and itemized energy consumption for each building type in the three regions were collected and sorted. The data was then used as base data to calibrate the models. For calibration, we conducted a first-time simulation and then adjusted the model (see following paragraphs) until the simulated data and real data matched closely. This calibrated model was then established as the base model for this climate region and building type. By using EnergyPlus, different retrofit technologies were then applied to the base models to calculate the energy savings achieved with each technology.

Climate data and building features

China is a vast country with very large regional differences in climate. The Code for Thermal Design of Civil Buildings (GB 0176-93) divides China into five climate zones: severe cold regions, cold regions, hot summer and cold winter regions, hot summer and warm winter regions, and mild regions. The three climate zones studied in this paper were Beijing (cold), Shanghai (hot summer and cold winter), and Guangzhou (hot summer and warm winter). Weather parameters for 5 climate zones in China are listed in Table 2. The climate data for EnergyPlus simulation was obtained from US Department of Energy weather files. Meanwhile, the thermal properties of various enclosure properties used in the models are listed in Tables 3 and 4.

Establishment of the typical office building model

In this research, the studied office building (Appendix 1: Fig. 1) was three floors high and 3600 m^2 (38,750 ft^2) in gross area. The height of the first floor was 6 m (19.7 ft) and the second and third floor were 3.5 m (11.5 ft) high. The building orientation faced south, and the window-wall ratios of all exposures were 40 %. The building adopted a typical office layout with the administrative areas located outside (each measuring 10 m in depth). In order to employ daylighting methods later, the model divided building use into four categories. And each floor of the office building area was divided into five thermal zones for the purpose of separate control since each zone has different exterior conditions and inner loads. The five thermal zones are the east zone, the west zone, the south zone, and the north zone as well as a core area where there are often few people in it. The internal-area divisions and specific model are shown in the following paragraph.

Table 3 Thermal characteristics of enclosure materials

Material	Density (kg/m^3)	Conductivity (W/mK)	Specific heat (kJ/kgK)
Steel-reinforced concrete	2500	1.740	0.92
Aerated concrete	700	0.220	1.05
Crushed stone concrete	2300	1.510	0.92
Cement mortar	1800	0.930	1.05
Lime-and-cement mortar	1700	0.870	1.05
Confined clay brick masonry	1800	0.810	1.05
Cement expanded perlite	800	0.260	1.17
EPS	30	0.042	1.38
XPS	35	0.034	1.40

In order to meet building legal requirements, the building enclosures have to be adapted to the Public Building Energy Efficiency Design Standard (GB50189-2005). The summer design temperature was 26 °C (78 °F) and the winter design temperature was 20 °C (70 °F). The HVAC operating schedule was set from 8 a.m. to 6 p.m. on working days (Monday to Friday). In addition, the external window adopted the most common alufer frame with double-pane glazing. The building parameters and indoor loads are elaborated in Tables 3 and 4. The HVAC system type used in this building was FCU along with an independent air manner system. An electric chiller and electric boiler were used as the cooling/heating source and a primary-pump

Table 2 Weather parameters for five climate zones in China

No.	Name of climate zone	Weather index
1	Severe cold zone	Average temperature in January≤−10 °C Average temperature in June ≤25 °C Average RH in June ≥50 %
2	Cold zone	Average temperature in January −10~0 °C Average temperature in June 18~28 °C
3	Hot summer cold winter zone	Average temperature in January 0~10 °C Average temperature in June 25~30 °C
4	Hot summer warm winter zone	Average temperature in January≥10 °C Average temperature in June 25~29 °C
5	Mild zone	Average temperature in June 18~25 °C Average temperature in January 0~13 °C

Table 4 Enclosure of typical office building model

Enclosure parameter	Cold region (Beijing)	Hot summer and cold winter region (Shanghai)	Hot summer and warm winter region (Guangzhou)
External-wall thermal transmittance (W/m^2 K)	0.57	0.99	1.50
Roof thermal transmittance (W/m^2 K)	0.60	0.69	0.89
External-window thermal transmittance (W/m^2 K)	2.70	3.20	3.20
External-window solar heat gain coefficient	0.81	0.81	0.81

constant-flow system was applied for air conditioning. The selection of systems was accomplished in EnergyPlus.

Establishment of the typical store building model

The store building model (Appendix 1: Fig. 2) was three floors high and had a gross area of 2700 m^2 (29,063 ft^2). The height of the first floor was 6 m (19.7 ft), and the second and third floors were 5 m (16.4 ft) high. The building orientation faced south, and the window-wall ratios of all exposures were 70 %. The internal zone was similar to that of a business area.

There are five options to calculate the exterior convective heat transfer coefficient (h_{out}) in EnergyPlus 8.0: Simple algorithm, DOE-2, TARP, MoWiTT, Adaptive Convection Algorithm. In this study, DOE-2 was used to calculate the exterior convective heat transfer coefficient according to the example files in EnergyPlus 8.0. "Conduction Transfer Function" method was used as interior surface convection algorithm. And the heat balance algorithm was "Conduction Transfer Function". The building terrain was in the city. Each floor of the shopping mall model has also five thermal zones. For the east, west, north, and south zones, each of them with a depth of 10 m, and there is also a core area which, different from office building model, has the same indoor setting (people, light, etc.) as the outer zones of the area. The enclosure settings were the same as that of the office building, meeting the requirements of Public Building Energy Efficiency Design Standard (GB50189-2005). The summer design temperature was 25 °C (77 °F) and the winter design temperature was 20 °C (70 °F). The HVAC operating schedule was set from 8 a.m. to 9 p.m. throughout the year. The indoor loads are shown in Tables 5 and 6. The HVAC system of this building was an all-air constant-air-low primary return air system. An electric chiller and electric boiler were used as the cooling/heating source and a primary-pump constant-flow system was applied for air conditioning. The selection of systems was accomplished in EnergyPlus.

Building data

To calibrate the building models, energy consumption data was sourced from a wide range of studies (Xue and Jiang 2004; Xie 1999; Zhao-phase et al. 2008). For office buildings in Beijing, electricity consumption was the average of investigative data from six samples, or 164 kWh/m^2 (heating energy not included). Heating energy was 60–120 kWh/m^2 (19,024-38,049 Btu/ft^2), or an average of 90 kWh/m^2 (28,537 Btu/ft^2). For Beijing stores, electricity consumption was the average of investigative data from 10 samples, or 293 kWh/m^2 (92,902 Btu/ft^2). Because the heating energy requirement was very small, no calibration was run for it. Electricity consumption for office buildings in Shanghai was the average of investigative data from 10 samples, or 119 kWh/m^2 (37,732 Btu/ft^2) (heating energy not included). Heating energy was 14 kWh/m^2 (4439 Btu/ft^2). Electricity consumption for Shanghai stores was the average of investigative data from several samples, or 290 kWh/m^2 (91,951 Btu/ft^2). Because the heating energy requirement was very small, no calibration was run for it. For office buildings in Guangzhou,

Table 5 Indoor setting for the office building model

Operating time	Fresh air (m^3/h p)	Occupant density (m^2/person)	Lighting power (W/m^2)	Equipment power (W/m^2)
8 a.m.–6 p.m.	30	0.17	18	15

Table 6 Indoor settings for the store building model

Operating time	Fresh air (m^3/h p)	Occupant density (m^2/person)	Lighting power (W/m^2)	Equipment power (W/m^2)
8 a.m.–9 p.m.	20	0.25	19	13

electricity consumption was the average of investigative data from eight samples, or 121 kWh/m^2 (29,154 Btu/ft^2) (heating energy not included). Finally, electricity consumption for Guangzhou stores was the average of investigative data from several samples, or 230 kWh/m^2. A review of related references found no itemized HVAC system energy consumption data for Guangzhou, so the data from Beijing was used as the reference because energy consumption for stores was similar throughout the different climate zones.

Calibration of the models

We first calibrated the monthly end use of cooling, heating and lighting. After the monthly data was calibrated, we further compared the annual energy use. It is worth mentioning that everything was compared in terms of site energy. Several references including ASHRAE Guideline 14-2002, the International Performance Measurement and Verification Protocol (IPMVP), and the Federal Energy Management Project (FEMP) were used to determine an acceptable calibration error (2002). Using these standards, it was established that an acceptable simulation could have at most an error of 10 % between the measured yearly energy consumption data and the simulated data (model testing was conducted on the basis of yearly whole-building test data because the monthly data available for the three climate zones was not comprehensive enough). To establish an accurate model, calibration was conducted by adjusting climate parameters, internal load settings, and HVAC system settings among others. It should be noted that some items like elevator energy use could not be simulated, and were excluded from the calibration process. In order to verify the calibration process, the simulated data on yearly energy consumption per unit area in the building models was compared to the source data. Calibrated results of each item are shown in the following paragraph:

This study focused on the energy reduction from each retrofitting methods rather than the absolute value of energy consumption. However, the total energy consumption is presented in Tables 7 and 8, when we perform model calibration. As Tables 7 and 8 show, the errors between the base models' simulation data and real testing data were within 10 % for all six models, indicating that the base models were qualified. What should be noted is that the models were calibrated on an average of energy consumptions recorded in different buildings (with different S/V ratios, window areas, envelopes, etc.). In this paper, we are not calibrating against one single building, but the average one.

Simulation error

Based on the calibration results, there were still deviations from the typical model data obtained in EnergyPlus and the real building data. For example, the model of a store building in Guangzhou had an error of 8 %. Some of this could be attributed to differences or difficulties in modeling exact building orientations and shapes; enclosure materials; occupant, equipment and lighting loads; divisions of space; performance curves of terminal devices; and cooling/heating system performances. Although there were some errors, the models were acceptable under the FEMP standard and were used to analyze the effect of different retrofit methods when applied to these base models.

Table 7 Calibrated energy consumption of office building base models

Region	Actual overall energy (kWh/m^2)	Simulated overall energy (kWh/m^2)	Error (%)	Actual heating energy (kWh/m^2)	Simulated heating energy (kWh/m^2)	Error (%)
Beijing	232.66	233.31	0.28	90.00	88.10	2.10
Shanghai	119.00	122.26	2.54	14.00	14.66	4.70
Guangzhou	112.25	115.41	2.82	/	/	/

Table 8 Calibrated energy consumption of store building base models

Region	Actual overall energy (kWh/m^2)	Simulated overall energy (kWh/m^2)	Error (%)	Heating energy (kWh/m^2)
Beijing	293.00	301.52	4.42	3.64
Shanghai	290.00	303.40	4.62	0.12
Guangzhou	220.80	238.55	8.04	/

Analysis of retrofit methods

Energy savings

First, the various retrofit methods were analyzed according to their ability to save energy, using the yearly energy-saving rate, R, as the indicator. This rate is defined as:

$$R = \frac{C_{\mathrm{b}} - C_a}{C_b} \qquad (1)$$

where C_b is the yearly energy consumption (GJ) before the retrofit and C_a is the yearly energy consumption (GJ) after the retrofit. Simulations of the building models were run in EnergyPlus under different scenarios and modules (180 different modules) to calculate the energy consumption before and after the retrofit. Tables 9 and 10 highlight the most and least effective retrofit methods for the six scenarios.

Cost savings

The retrofit methods were then subjected to a cost analysis to determine whether they were feasible in a real-life scenario. The yearly benefit equation converts the energy savings of each method into monetary values:

$$S = E_b - E_a \qquad (2)$$

where S is the yearly cost savings (RMB) after retrofitting, E_b is the yearly operating cost (RMB) of the base building, and E_a is the yearly operating cost (RMB) after applying the energy-saving method. To calculate the yearly cost savings, the yearly electricity and gas savings were converted into RMB values depending on local energy prices, as shown in Table 11. The data source is obtained by consulting local engineers in several construction contractors in China. The cost does vary year to year and the current cost is based on the year when the paper is written.

Next, the payback period was calculated as a simple payback, ignoring the time value of money. The payback period in years, PBP, is defined according to the following equation:

$$\mathrm{PBP} = \frac{C}{S} \qquad (3)$$

where C is the retrofit cost (RMB) and S is the yearly cost savings (RMB) after retrofitting. The cost estimates (including materials and labor) used in this study was provided by engineers in Shanghai, although there could be slight differences among the three locations.

Comprehensive evaluation and results

Payback period method

Finally, we conducted a comprehensive evaluation of each method, rating each one based on a combination of its energy-saving rate and economic value. Tables 12 and 13

Table 9 Effective methods for office and store buildings

Building type	Beijing (cold region)	Shanghai (hot summer and cold winter region)	Guangzhou (hot summer and warm winter region)
Office building	• Daylighting • Exhaust air heat recovery • Energy-efficient lamps	• Daylighting • Energy-efficient lamps	• Daylighting • Energy-efficient lamps
Store building	• Low-solar-gain low-E glass • Movable louver shading • Movable roller shutter shading • Energy-efficient lamps	• Low-solar-gain low-E glass • Movable louver shading • Movable roller shutter shading • Energy-efficient lamps	• Low-solar-gain low-E glass • Energy-efficient lamps

Table 10 Less effective methods for office and store buildings

Building type	Beijing (cold region)	Shanghai (hot summer and cold winter region)	Guangzhou (hot summer and warm winter region)
Office building	• Exterior insulation of walls and roof • Thermal reflective film	• Exterior insulation of walls and roof	• Exterior insulation of walls and roof • High-solar-gain low-E glass
Store building	• Exterior insulation of walls and roof	• Exterior insulation of walls and roof • Exhaust air heat recovery • Cooling tower free cooling (indirect)	• Exterior insulation of walls and roof • Exhaust air heat recovery • Cooling tower free cooling • Fresh air free cooling

show how the ratings are defined for yearly energy-saving rate and payback period. With these rating categories, we created a comprehensive evaluation of the retrofit methods for each model in Tables 14, 15, 16, 17, 18, and 19 (the labeling of methods is given in Table 1). The energy-saving rate decreases from left to right and the economic value decreases from top to bottom. Thus, the most effective methods (highlighted in italics) can be found in the top left corner of each table. For office buildings in Beijing, the best methods were exhaust air heat recovery, daylighting, and energy-efficient lamps. For Beijing stores, the best methods were low-solar-gain low-E glass and energy-efficient lamps. For office buildings in Shanghai, the best methods were daylighting and energy-efficient lamps. For Shanghai stores, the best methods were low-E glass and energy-efficient lamps. For office buildings in Guangzhou, the best methods were daylighting and energy-efficient lamps. For Guangzhou stores, the best methods were energy-efficient lamps and movable roller shutter shading (translucent).

Cost of conserved energy

The cost of conserved energy (CCE) is an investment statistic that simplifies comparison of conservation measures among themselves and against competing energy supplies. A conservation measure is cost-effective if its CCE is less than the price of the energy the measure displaces. The CCE is especially useful when future energy price is uncertain. There are two investment decision rules associated with the cost of conserved energy. The first rule is to choose the measure with the lowest cost of conserved energy. The second rule is to implement all conservation measures with a cost of conserved energy less than the price of the avoided energy.

Table 11 Energy prices for Beijing, Shanghai, and Guangzhou

Region	Electricity (RMB/kWh)	Natural gas (RMB/m^3)
Beijing	0.7885	2.280
Shanghai	0.8850	2.500
Guangzhou	1.0874	/

$$\mathrm{CCE} = \frac{\text{Investment}}{\text{Annual Energy Savings}} \cdot \frac{d}{1-(1+d)^{-n}} \tag{4}$$

Formula (4) shows how the cost of conserved energy (CCE) is calculated, within it we must now specify the discount rate, d, and the amortization time n (to keep consistent dimensions, the amortization time, discount rate, and energy savings must all be expressed in year).

Table 13 shows how the ratings are defined using CCE rating system. With these rating categories, we created a comprehensive evaluation of the retrofit methods for each model in Table 20 (the labeling of methods is given in Table 1). The CCE value decreases from left to right and the most cost-effective methods are marked in italics. According to the CCE rating results, many of the most cost-effective methods for the six kinds of building models are in accordance with the PBP rating system, like B1/B2/D1/D2 for Beijing Office, A6/D1 for Beijing Store, D2/D1 for Shanghai Office, A6/D1 for Shanghai Store, D2/D1 for Guangzhou Office, and D2/A10 for Guangzhou Store.

Table 12 Energy ratings of retrofit methods

Yearly energy-saving rate	Energy rating
$R \geq 10$ %	Very high
5 %$\leq R <$10 %	High
1 %$\leq R <$5 %	Moderate
$R <$1 %	Low

Table 13 Economic ratings of retrofit methods

PBP rating method	
Payback period (years)	Economic rating
PBP≤5	Good
5<PBP≤30	Moderate
PBP>30	Poor
CCE rating method	
CCE (¥/kWh)	Economic rating
CCE≤0.5	Excellent
0.5<CCE≤1	Good
1<CCE≤5	Moderate
CCE>5	Poor
NPV rating method	
Present Value (¥)	Economic rating
Present value>0	Economically favorable
Present value≤0	Economically unfavorable
IRR rating method	
p^*	Economic rating
$p^*>0$	Economically favorable
$p^*\leq 0$	Economically unfavorable

Detailed calculation results are shown in Appendix 2, Tables 31, 32, 33, 34, 35 and 36.

Net present value

The net present value (NPV) sums the discounted cash flows; it integrates and converts at the same time amounts of money (e.g., incomes, expenses, etc.) of various time periods (Nikolaidis et al. 2009). The formula that is used for the determination of the NPV is:

$$\mathrm{NPV} = -C_0 + \sum_{t=1}^{n} \frac{F_t}{(1+p)^t} \tag{5}$$

where t is the time period, usually a year, F_t the net cash flow for year t, i.e. F_t=B_t−C_t, B_t the benefit (inflows) for year t, C_t the cost (outflows) for year t; the value C_0 reflects the initial investment, p the discount rate, and n is the number of years of the investment's lifetime or, differently, the number of years for which the economic evaluation is requested. It is assumed that the various net cash flows of Eq. (5) are collected at the end of the time periods, i.e. at the end of years. An investment should be realized only if NPV>0, while in case alternative investments are compared, the best of them would be the one with the higher NPV.

The discount rate p is the cost of capital when evaluating investments similar in risk to this investment portfolio, which is 4 % in this process. This discount rate was chosen following the methodology used by Nikolaidis et al. (2009). As a result of the severe downturn in the global economy since 2008, nominal interest rates have been declining rapidly over the past few years in many countries. This has pushed down major interest rates and it is believed that it had also affected the cost of capital to major energy investments. Thus a cost of capital, or a discount rate, of 4 % is believed to be acceptable in this paper. Finally, it is worth mentioning an inverse relation between the cost of capital p and NPV: the increase of p leads to a decrease in NPV, when all other parameters remain constant.

Table 13 shows how the ratings are defined using NPV rating system. With these rating categories, we

Table 14 Evaluation of Beijing offices

	Savings			
	Very high	High	Moderate	Low
Good economy	*B1/B2/D2*	*D1*	C1	/
Moderate economy	/	/	A6/A10	A1/A2/A3/A4
Poor economy	/	/	A5/A8/A9	A7

Table 15 Evaluation of Beijing stores

	Savings			
	Very high	High	Moderate	Low
Good economy	*A6*	*D1*	B3/B4/B5/B6/C1	/
Moderate economy	A10	A9/B2	A5/A7/A8/B1	A1/A2/A3/A4
Poor economy	/	/	/	/

Table 16 Evaluation of Shanghai offices

	Savings			
	Very high	High	Moderate	Low
Good economy	*D2*	*D1*	C1	/
Moderate economy	/	B2	A6/A7/A10/B1	A1
Poor economy	/	/	A5/A8/A9	A2/A3/A4

Table 17 Evaluation of Shanghai stores

	Savings			
	Very high	High	Moderate	Low
Good economy	*A6*	*D1*	B2/B3/B4/B5/C1	A1/A2/A3/B1
Moderate economy	A8/A10	A9	A5/A7	A4/B6
Poor economy	/	/	/	/

created a comprehensive evaluation of the retrofit methods for each model in Table 21 considering a cost of capital of 4 % (the labeling of methods is given in Table 1). Most of the cost-effective methods for the six kinds of building models are in accordance with the PBP and CCE rating system, like B1/B2/D1/D2 for Beijing Office, A6/D1 for Beijing Store, D2/D1 for Shanghai Office, A6/D1 for Shanghai Store, D2/D1 for Guangzhou Office, and D2/A10 for Guangzhou Store. But it should be noted that there might be a change of order because different rating systems focus on different things. The cost of the retrofits and yearly saved cost may influence the rating system parameters in different ways since they are calculated according to different formulas. What also should be noted is that the lifetimes of all the retrofit methods are not the same. For example, for envelope retrofit methods like EPS or XPS, it was assumed that their lifetime can reach 30 years (which is the same as the building), whereas for shading devices, the lifetime was assumed to be shorter (15 years) since they are less vulnerable than insulation materials like EPS or XPS, and they located outside of building, and for energy-efficient lamps, the lifetime is 10,000 h which is known to all. Since the retrofit methods have different lifetimes, we should calibrate the NPV according to their lifetimes. Detailed calculation results are shown in Appendix 2, Tables 37, 38, 39, 40, 41, and 42.

Table 18 Evaluation of Guangzhou offices

	Savings			
	Very high	High	Moderate	Low
Good economy	*D2*	*D1*	C1	/
Moderate economy	/	/	A6/A7/A10/B1/B2	/
Poor economy	/	/	A8/A9	A1/A2/A3/A4/A5

Table 19 Evaluation of Guangzhou stores

	Savings			
	Very high	High	Moderate	Low
Good economy	*D2*	*A10/D1*	B1/B2/B4/C1	A1/A2/A3/B3/B5
Moderate economy	/	A6/A8/A9	A5/A7	A4
Poor economy	/	/	/	B6

Internal rate of return

The internal rate of return (IRR) evaluation method aims at the determination of the discount rate p^* that renders the present value of future discounted net cash flows of an investment equal to the initial cash outflow (initial investment), for the total years of evaluation. The discount rate p^* is determined from the following equation:

$$\mathrm{NPV} = -C_0 + \sum_{t=1}^{n} \frac{F_t}{(1+p^*)^t} = 0 \qquad (6)$$

The IRR is the discount rate p^* that renders the examined investment marginal and constitutes the higher interest that can be paid by an investor for finding the capital that is required for an investment. When the examined investments are economically independent, one can find attractive all investments that present an IRR greater than the minimum acceptable interest rate by evaluating them with this method. Besides, the most attractive investment is the one that presents the higher IRR. Table 13 shows how the ratings are defined using IRR rating system. With these rating categories, we created a comprehensive evaluation of the retrofit methods for each model in Table 22 (the labeling of methods is given in Table 1). As shown in Table 22, the most cost-effective retrofit methods are in accordance with PBP, CCE, and NPV rating systems except for that there might be a switch of order. Detailed calculation results are shown in Appendix 2, Tables 43, 44, 45, 46, 47, and 48.

Uncertainty analysis

A building retrofit is subject to many uncertainty factors, such as uncertainty in savings estimation, energy use

Table 20 Evaluation of all models using CCE rating system

	Savings			
Region	Excellent	Good	Moderate	Poor
Beijing Office	*D2/D1/B1/B2/C1*	/	A4/A2/A3/A1/A6/A10	A9/A8/A7/A5
Beijing Store	*C1/D1*	*A6/A10/A7*	B1/A8/A2/A1/A3/B2/A9/A5/A4	/
Shanghai Office	*D2/D1/C1*	*B2/B1/A1*	A7/A6/A10	A4/A2/A9/A8/A3/A5
Shanghai Store	*D1/A1/C1/A2/A6/A3*	*B2/D2/B1/A4/A10*		A7/A9/A8/A5
Guangzhou Office	*D2/D1/C1*	/	B1/B2/A7/A6/A10	A9/A1/A8/A5/A2/A4/A3
Guangzhou Store	*D2/A10/B1/A1/B2/C1/A3*	*A2/D1/A6*	A4/A7/A9/A8/A5	/

measurements, weather forecast, changes of energy consumption patterns, system performance degradations, etc. These uncertainty factors result in the situation that investment in building retrofits is highly uncertain. However, as for this paper, the uncertainty comes from different parameters we used in the simulations. For example, the savings of heat recovery system depend highly on the ventilation rate, and thus we simulated different scenarios with different ventilation rates and this is not a full-scale stock level uncertainty analysis, so we did not perform detailed uncertainty analysis.

In addition, another thing that is uncertain about the results is that one retrofit method may have influence on the other. When we use more daylight, for example, though we can lower the electricity demand, we also get more solar heat, which can lead to increased solar heat gain and thus to increased cooling load and more electricity consumption for HVAC system. However, there are too many combinations and the main point of this analysis is to rank the effectiveness of each method, so we did not perform further combination of the retrofit methods.

Conclusions

Energy-saving retrofits of large-scale public buildings are especially important for China as the country requires increasing amounts of energy to fuel its fast-paced growth. From a survey of the literature, we found that systematic analyses of energy retrofit methods for different climate zones and different types of buildings had been conducted in America and Europe, but those studies only focused on their respective regions or countries. In China, very little research has been done on this area and it is still not clear which methods work better than others. This lack of a systematic survey of retrofit methods presents a barrier to the spread of building retrofit strategies in this country. With this report, we hope to help lower that barrier by developing a comprehensive analysis of retrofit methods for office buildings and stores in three representative climate zones of China.

Only commonly used building retrofit methods were selected. We collected itemized energy consumption data from office buildings and stores in Beijing, Shanghai, and Guangzhou to establish and calibrate base models in EnergyPlus (the base models have errors within 10 %,

Table 21 Evaluation of all models using NPV rating system

Region	Positive present value	Negative present value
Beijing Office	D2/B2/D1/B1/C1/A4	A2/A3/A1/A7/A6/A5/A9/A10/A8
Beijing Store	A6/A10/A8/A9/C1/D1/A7/B2/B1/A5/A4/A3/A2/A1	/
Shanghai Office	D2/C1/B2/D1/B1/A10/A9	A1/A2/A4/A5/A3/A7/A8/A6
Shanghai Store	A6/A10/A8/A9/D1/A7/B2/D2/C1/B1/A4/A3/A2/A1	A5
Guangzhou Office	D2/D1/C1/B2/B1	A1/A2/A4/A4/A7/A6/A9/A5/A10/A8
Guangzhou Store	A10/A6/B2/A9/A8/D2/B1/A7/C1/D1/A3/A2/A4/A1	A5

The higher the NPV, the better economic effect the technology has, and from the left to right, the NPV becomes smaller, which means the technology is less favorable

Table 22 Evaluation of all models using IRR rating system

Region	$p^*>0$	$p^*\leq 0$
Beijing Office	D2/D1/C1/B1/B2/A4/A2/A1/A3	A6/A10/A9/A8/A7/A5
Beijing Store	C1/D1/A6/A10/B1/A1/A2/B2/A9/A7/A3/A8/A4/A5	/
Shanghai Office	D2/C1/D1/B1/A10/A9/A1/A4	A2/A5/A3/A8/A7/A6
Shanghai Store	D1/C1/A1/A6/A2/A3/B2/D2/B1/A4/A10/A7/A9/A8/A5	/
Guangzhou Office	D2/C1//D1/B1/B2	A6/A1/A7/A2/A10/A4/A9/A8/A3/A5
Guangzhou Store	D2/A10/B1/A1/B2/A3/A6/A2/D1/A4/A7/A9/A8	A5

The higher the IRR, the better economic effect the technology has, and from the left to right, the IRR becomes smaller, which means the technology is less favorable

which can be acceptable under the FEMP standard). After simulating many energy-saving methods (100 sets of simulation), we compared these simulation results with those of the base models and determined the energy-saving rate and economic feasibility of each method. Finally, we conducted a comprehensive evaluation to rate each method taking into account their economic benefits and energy-saving rates. From the results of this study, we have drawn the following conclusions:

1. For buildings whose walls and roofs met the requirements of the Public Building Energy-Saving Design Standard (GB50189-2005), additional insulation was inefficient and uneconomic to some degree. We note that applying thicker insulation in colder regions, such as Beijing, increases the cost; it is more advantageous since payback time shortens. While the optimum insulation thickness for hotter climates becomes lower. Choosing a thickness value apart from the optimum one will increase the total cost. Therefore, even for public buildings with no insulation in Shanghai and Guangzhou, the insulation of walls had no significant benefit.
2. The energy savings for exterior shading devices, such as the louver shading and roller shutter shading, were very high, but the installation costs were also high. Significant retrofit opportunities will exist in this area if lower-cost and durable shading devices are developed.
3. Low-E glass appeared to be suitable under most conditions and was especially effective in Shanghai and Guangzhou where high cooling costs were reduced. Reflective window films were not very useful in any climate zones.
4. VFD control of pumps saved little energy. However, it is a very popular and easy mechanical system retrofit because of its low initial cost and short payback period.
5. Cooling tower free cooling was applicable in buildings that need cooling in winter and in climates with long swing seasons. This method had a low initial cost and a short payback period. This method worked better in Beijing than in Shanghai and Guangzhou.
6. Exhaust air heat recovery was most suitable for buildings with a high heating load in winter, such as office buildings in Beijing. For stores in Beijing, the energy-saving rate was moderate, since no heating was needed in these stores during winter. This method was less effective in Shanghai and Guangzhou during summer where indoor and outdoor temperature differences were less pronounced.
7. Lighting system retrofits had very high energy savings for both office buildings and stores because artificial lighting is used throughout the year whereas heating and cooling are only used for parts of the year. Daylighting retrofitting is very cost-effective in theory, but practically it is very hard to implement. We observed very few daylighting retrofitting projects in China for a number of reasons. First, it is very hard to meter the savings. Second, owners normally are very reluctant to do anything in occupied areas and disturb the day-to-day business. If permitted, engineers should consider performing more daylighting retrofits (light tubes and window reflective shading) rather than mechanical system retrofits.

Future work

The accuracy of these results greatly depends on the rationality of the building parameters used in creating the base models. The conclusions were obtained from the calculations based on limited conditions, but with more accurate and complete energy consumption data in the future, we can establish and develop more reliable models and analyses. In this study, we only looked at two types of buildings, whereas there are many others such as hotels, hospitals, gymnasiums, and schools that use energy very differently. More research needs to be done for examining the effectiveness of retrofit methods on this broader range of building types. Currently, building simulation software is limited, so some energy-saving methods like air loop retrofits—duct static pressure reset, and underfloor airflow systems—were not discussed in this paper. With more advanced simulation tools in the future, we should be able to address these methods. Finally, simulations can only provide theoretical calculations, indicating that savings achieved in the field may be different from what is predicted. Thus, it is necessary to measure energy savings achieved in actual projects where a best-practice database may be of use. With the ever-growing demand for energy, retrofitting existing buildings represents an enormous opportunity to minimize energy consumption. By providing guidance on effective retrofitting strategies, this research serves as a step towards realizing that potential.

Appendix 1

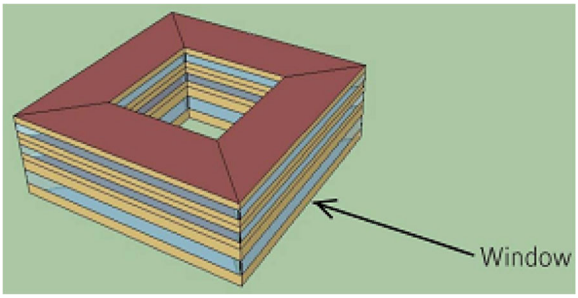


Fig. 1 Typical office building model

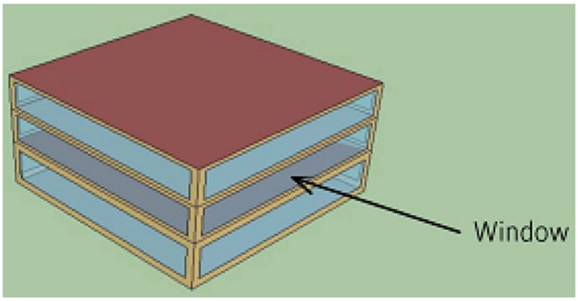


Fig. 2 Typical store building model

Fig. 3 Beijing office building model calibration. *AHU* air handling unit

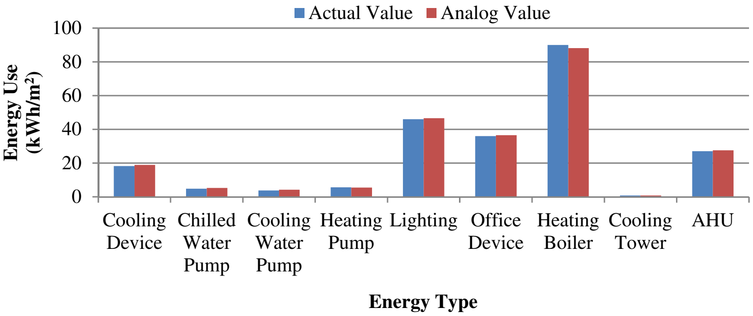


Fig. 4 Shanghai office building model calibration

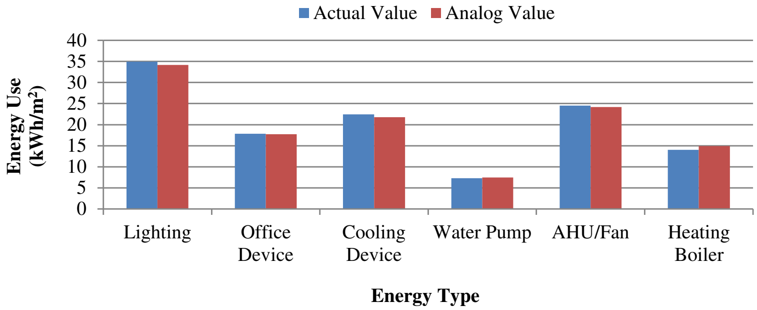


Fig. 5 Guangzhou office building model calibration

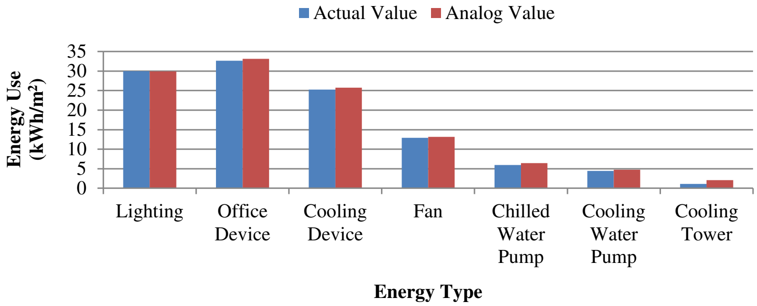


Fig. 6 Beijing store building model calibration

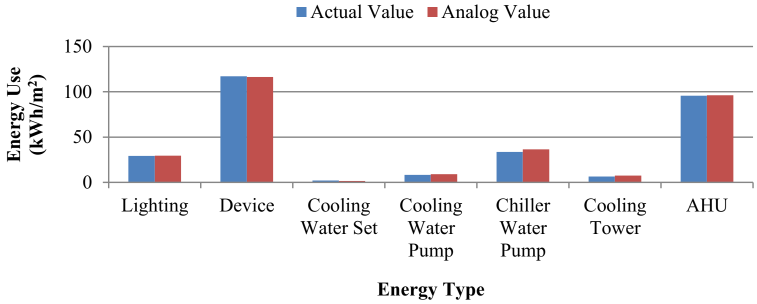


Fig. 7 Shanghai store building model calibration

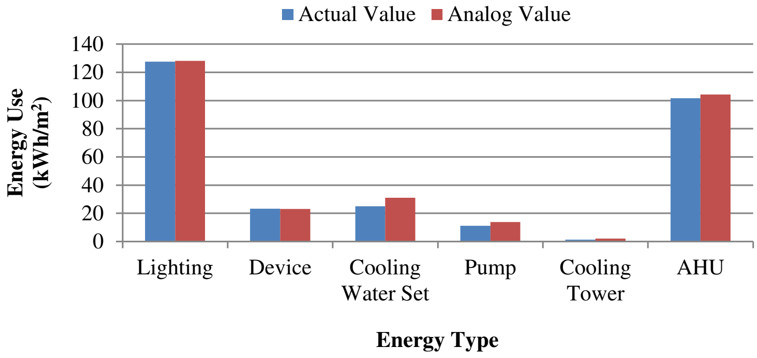
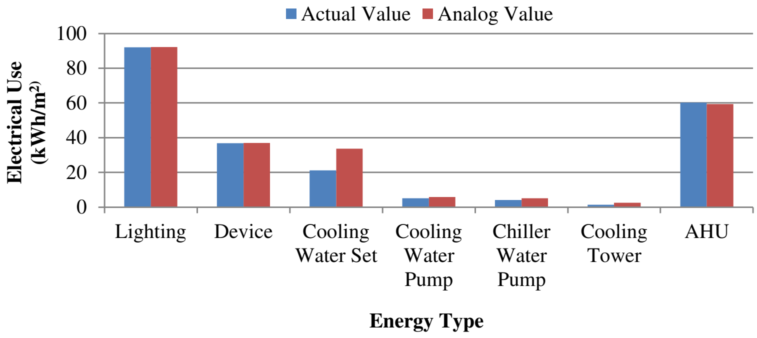


Fig. 8 Guangzhou store building model calibration



Appendix 2

Table 23 Costs of common retrofit methods

Method	Cost
EPS wall insulation	400RMB/m^3 (US$1.77/ft^3)
XPS roof insulation	550RMB/m^3 (US$2.44/ft^3)
High-solar-gain low-E glass	260RMB/m^3 (US$1.15/ft^3)
Low-solar-gain low-E glass	250RMB/m^3 (US$1.11/ft^3)
Window reflective film	120RMB/m^3 (US$0.53/ft^3)
Movable louver shading	500RMB/m^3 (US$2.21/ft^3)
Roller shutter shading (translucent)	400RMB/m^3 (US$1.77/ft^3)
Roller shutter shading (opaque)	300RMB/m^3 (US$1.33/ft^3)
Exhaust air heat recovery (standard fresh airflow)	50,000–100,000RMB (US$221.4/ft^3- US$442.9/ft^3)
Exhaust air heat recovery (high fresh airflow)	None
Cooling tower free cooling (direct)	20,000RMB (US$88.6)
Cooling tower free cooling (indirect)	60,000RMB (US$1.77/ft3)
Pump variable flow	1,000RMB/kW (US$0.046/Btu) converter
Energy-efficient lamps	70RMB/lamps (US$0.0032) (set)
Daylighting	1,000RMB/sensor (US$1.77) (piece)

Table 24 Payback period of Beijing offices

Method	Energy-saving rate (%)	Saved cost (RMB)	Retrofit cost (RMB)	Payback period (years)
Exterior wall 10 mm EPS	0.15	278	7520	27.05
Exterior wall 20 mm EPS	0.33	621	15,040	24.22
Exterior wall 30 mm EPS	0.48	928	22,560	24.31
Roof 30 mm XPS	0.77	1514	19,800	13.08
High-solar-gain low-E glass	1.16	5798	322,400	55.61
Low-solar-gain low-E glass	1.06	14,103	310,000	21.98
Window reflective film	−0.28	2894	148,800	51.42
Movable louver shading	2.84	18,787	620,000	33.00
Roller shutter shading (translucent)	1.74	11,505	372,000	32.33
Roller shutter shading (opaque)	2.96	19,607	496,000	25.30
Exhaust air heat recovery (standard fresh airflow)	14.60	30,790	50,000	1.62
Exhaust air heat recovery (high fresh airflow)	16.02	46,532	80,000	1.73
VFD pumps	2.00	13,227	16,000	1.21
Energy-efficient lamps	6.28	46,637	46,452	1.00
Daylighting	17.10	125,911	70,452	0.56

Table 25 Retrofit description

Method	Before retrofit	After retrofit
Exterior wall 10 mm EPS	*U* value 0.57 W/m^{2}K	*U* value 0.48 W/m^{2}K
Exterior wall 20 mm EPS	*U* value 0.57 W/m^{2}K	*U* value 0.44 W/m^{2}K
Exterior wall 30 mm EPS	*U* value 0.57 W/m^{2}K	*U* value 0.399 W/m^{2}K
Roof 30 mm XPS	*U* value 0.6 W/m^{2}K	*U* value 0.392 W/m^{2}K
High-solar-gain low-E glass	SC=0.93	SC≥0.5
Low-solar-gain low-E glass	SC=0.93	SC<0.5
Movable louver shading	SC=0.93	/
Roller shutter shading (translucent)	SC=0.93	/
Roller shutter shading (opaque)	SC=0.93	/
Exhaust air heat recovery (standard fresh airflow)	0.763 kW/ton	0.65 kW/ton
Energy-efficient lamps	18 W/m^2	16 W/m^2

Table 26 Payback period of Beijing stores

Method	Energy-saving rate (%)	Saved cost (RMB)	Retrofit cost (RMB)	Payback period (years)
Exterior wall 10 mm EPS	0.07	350	2272	6.49
Exterior wall 20 mm EPS	0.13	631	4544	7.20
Exterior wall 30 mm EPS	0.17	854	6816	7.98
Roof 30 mm XPS	0.37	1753	14,850	8.47
High-solar-gain low-E glass	4.67	29,903	320,320	10.71
Low-solar-gain low-E glass	11.29	81,356	308,000	3.79
Window reflective film	3.18	22,793	147,840	6.49
Movable louver shading	13.21	85,703	616,000	7.19
Roller shutter shading (translucent)	8.66	56,102	369,600	6.59
Roller shutter shading (opaque)	13.93	90,349	492,800	5.45
Exhaust air heat recovery (standard fresh airflow)	1.50	4995	30,000	6.01
Exhaust air heat recovery (high fresh airflow)	6.57	6799	50,000	7.35
VFD pumps	2.40	15,570	12,500	0.73
Energy-efficient lamps	2.84	18,740	34,839	0.71

Table 27 Payback period of Shanghai offices

Method	Energy-saving rate (%)	Saved cost (RMB)	Retrofit cost (RMB)	Payback period (years)
Exterior wall 10 mm EPS	0.15	640	7520	11.75
Exterior wall 20 mm EPS	0.22	395	15,040	38.08
Exterior wall 30 mm EPS	0.36	504	22,560	44.76
Roof 30 mm XPS	0.19	564	19,800	35.11
High-solar-gain low-E glass	1.34	3959	322,400	81.43
Low-solar-gain low-E glass	3.68	16,062	310,000	19.30
Window reflective film	1.29	7990	148,800	18.62
Movable louver shading	4.13	16,997	620,000	36.48
Roller shutter shading (translucent)	2.46	10,519	372,000	35.36
Roller shutter shading (opaque)	4.43	18,147	496,000	27.33
Exhaust air heat recovery (standard fresh airflow)	3.68	6490	50,000	7.70
Exhaust air heat recovery (high fresh airflow)	5.56	10,386	80,000	7.70
VFD pumps	1.58	7080	11,000	1.55
Energy-efficient lamps	6.28	46,637	46,452	1.00
Daylighting	17.10	125,911	70,452	0.56

Table 28 Payback period of Shanghai stores

Method	Energy-saving rate (%)	Saved cost (RMB)	Retrofit cost (RMB)	Payback period (years)
Exterior wall 10 mm EPS	0.20	1196	2272	1.90
Exterior wall 20 mm EPS	0.27	1861	4544	2.44
Exterior wall 30 mm EPS	0.34	2350	6816	2.90
Roof 30 mm XPS	0.34	2901	14,850	5.12
High-solar-gain low-E glass	3.22	23,149	320,320	13.84
Low-solar-gain low-E glass	10.70	77,483	308,000	3.98
Window reflective film	3.25	23,947	147,840	6.17
Movable louver shading	11.52	83,551	616,000	7.37
Roller shutter shading (translucent)	8.00	56,775	369,600	6.51
Roller shutter shading (opaque)	12.11	87,829	492,800	5.61
Exhaust air heat recovery (standard fresh airflow)	13.93	7751	30,000	3.87
Exhaust air heat recovery (high fresh airflow)	2.30	13,352	50,000	3.74
VFD pumps	1.91	13,867	0	0.00
Energy-efficient lamps	3.45	26,444	0	0.00
Daylighting	1.61	11,682	9000	0.77

Table 29 Payback period of Guangzhou offices

Method	Energy-saving rate (%)	Saved cost (RMB)	Retrofit cost (RMB)	Payback period (years)
Exterior wall 10 mm EPS	0.04	187	7520	40.21
Exterior wall 20 mm EPS	0.03	130	15,040	115.69
Exterior wall 30 mm EPS	0.02	79	22,560	285.57
Roof 30 mm XPS	0.02	106	19,800	186.79
High-solar-gain low-E glass	0.81	3649	322,400	88.35
Low-solar-gain low-E glass	4.33	19,555	310,000	15.85
Window reflective film	1.88	8470	148,800	17.57
Movable louver shading	3.98	17,954	620,000	34.53
Roller shutter shading (translucent)	2.55	11,499	372,000	32.35
Roller shutter shading (opaque)	4.15	18,746	496,000	26.46
Exhaust air heat recovery (standard fresh airflow)	1.52	6875	50,000	7.27
Exhaust air heat recovery (high fresh airflow)	2.09	10,478	80,000	7.64
VFD pumps	2.61	11,786	12,000	1.02
Energy-efficient lamps	9.80	44,242	46,452	1.05
Daylighting	25.23	113,923	70,452	0.62

Table 30 Payback period of Guangzhou stores

Method	Energy-saving rate (%)	Saved cost (RMB)	Retrofit cost (RMB)	Payback period (years)
Exterior wall 10 mm EPS	0.16	1099	2272	2.07
Exterior wall 20 mm EPS	0.25	1725	4544	2.63
Exterior wall 30 mm EPS	0.31	2145	6816	3.18
Roof 30 mm XPS	0.25	1719	14,850	8.64
High-solar-gain low-E glass	2.89	20,256	320,320	15.81
Low-solar-gain low-E glass	9.71	68,011	308,000	4.53
Window reflective film	2.79	19,546	147,840	7.56
Movable louver shading	9.31	65,235	616,000	9.44
Roller shutter shading (translucent)	6.31	44,182	369,600	8.37
Roller shutter shading (opaque)	9.77	68,419	492,800	7.20
Exhaust air heat recovery (standard fresh airflow)	1.53	10,684	30,000	2.81
Exhaust air heat recovery (high fresh airflow)	2.33	16,583	50,000	3.02
VFD pumps	0.60	4193	0	0.00
Energy-efficient lamps	1.03	7376	0	0.00
Daylighting	1.64	11,490	10,000	0.87

Table 31 CCE for Beijing office building

	Technologies	Investment (RMB)	Saved cost (RMB)	Annual energy savings (kWh/year)	*n*	CCE
A1	Exterior wall 10 mm EPS	7520	278	314.1243	30	3.65
A2	Exterior wall 20 mm EPS	15,040	621	701.6949	30	3.26
A3	Exterior wall 30 mm EPS	22,560	928	1048.588	30	3.28
A4	Roof 30 mm XPS	19,800	1514	1710.734	30	1.76
A5	High-solar-gain low-E glass	322,400	5798	6551.412	15	8.42
A6	Low-solar-gain low-E glass	310,000	14,103	15,935.59	15	3.33
A7	Window reflective film	148,800	2894	3270.056	15	7.78
A8	Movable louver shading	620,000	18,787	21,228.25	20	4.67
A9	Roller shutter shading (translucent)	372,000	11,505	13,000	20	4.57
A10	Roller shutter shading (opaque)	496,000	19,607	22,154.8	20	3.58
B1	Exhaust air heat recovery (standard fresh airflow)	50,000	30,790	34,790.96	30	0.22
B2	Exhaust air heat recovery (high fresh airflow)	80,000	46,532	52,578.53	30	0.23
C	VFD pumps	16,000	13,227	14,945.76	15	0.23
D1	Energy-efficient lamps	46,452	46,637	52,697.18	10	0.18
D2	Daylighting	70,452	125,911	142,272.3	30	0.11

Table 32 CCE for Beijing store building

	Technologies	Investment (RMB)	Saved cost (RMB)	Annual energy savings (kWh/year)	CCE
A1	Exterior wall 10 mm EPS	2272	350	395	0.87
A2	Exterior wall 20 mm EPS	4544	631	713	0.97
A3	Exterior wall 30 mm EPS	6816	854	965	1.08
A4	Roof 30 mm XPS	14,850	1753	1981	1.14
A5	High-solar-gain low-E glass	320,320	29,903	33,789	1.62
A6	Low-solar-gain low-E glass	308,000	81,356	91,928	0.57
A7	Window reflective film	147,840	22,793	25,755	0.98
A8	Movable louver shading	616,000	85,703	96,840	1.02
A9	Roller shutter shading (translucent)	369,600	56,102	63,392	0.93
A10	Roller shutter shading (opaque)	492,800	90,349	102,089	0.77
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	4995	5644	0.81
B2	Exhaust air heat recovery (high fresh airflow)	50,000	6799	7682	0.99
C	VFD pumps	12,500	15,570	17,593	0.15
D1	Energy-efficient lamps	34,839	18,740	21,175	0.33

Table 33 CCE for Shanghai office building

	Technologies	Investment (RMB)	Saved cost (RMB)	Annual energy savings (kWh/year)	CCE
A1	Exterior wall 10 mm EPS	7520	640	723	1.58
A2	Exterior wall 20 mm EPS	15,040	395	446	5.13
A3	Exterior wall 30 mm EPS	22,560	504	569	6.03
A4	Roof 30 mm XPS	19,800	564	637	4.73
A5	High-solar-gain low-E glass	322,400	3959	4473	12.33
A6	Low-solar-gain low-E glass	310,000	16,062	18,149	2.92
A7	Window reflective film	148,800	7990	9028	2.82
A8	Movable louver shading	620,000	16,997	19,206	5.16
A9	Roller shutter shading (translucent)	372,000	10,519	11,886	5.00
A10	Roller shutter shading (opaque)	496,000	18,147	20,505	3.86
B1	Exhaust air heat recovery (standard fresh airflow)	50,000	6490	7333	1.04
B2	Exhaust air heat recovery (high fresh airflow)	80,000	10,386	11,736	1.04
C	VFD pumps	11,000	7080	8000	0.24
D1	Energy-efficient lamps	46,452	46,637	52,697	0.18
D2	Daylighting	70,452	125,911	142,272	0.08

Table 34 CCE for Shanghai store building

	Technologies	Investment (RMB)	Saved cost (RMB)	Annual energy savings (kWh/year)	CCE
A1	Exterior wall 10 mm EPS	2272	1196	1351	0.26
A2	Exterior wall 20 mm EPS	4544	1861	2103	0.33
A3	Exterior wall 30 mm EPS	6816	2350	2655	0.39
A4	Roof 30 mm XPS	14,850	2901	3278	0.69
A5	High-solar-gain low-E glass	320,320	23,149	26,157	2.09
A6	Low-solar-gain low-E glass	308,000	150,483	170,037	0.31
A7	Window reflective film	147,840	23,947	27,059	0.93
A8	Movable louver shading	616,000	83,551	94,408	1.04
A9	Roller shutter shading (translucent)	369,600	56,775	64,153	0.92
A10	Roller shutter shading (opaque)	492,800	87,829	99,242	0.79
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	7711	8713	0.52
B2	Exhaust air heat recovery (high fresh airflow)	50,000	13,352	15,087	0.50
C	VFD pumps	18,000	9867	11,149	0.28
D1	Energy-efficient lamps	26,452	26,444	29,880	0.18
D2	Daylighting	44,980	11,682	13,200	0.52

Table 35 CCE for Guangzhou Office building

	Technologies	Investment (RMB)	Saved cost (RMB)	Annual energy savings (kWh/year)	CCE
A1	Exterior wall 10 mm EPS	7520	187	211	5.42
A2	Exterior wall 20 mm EPS	15,040	130	147	15.59
A3	Exterior wall 30 mm EPS	22,560	79	89	38.49
A4	Roof 30 mm XPS	19,800	106	120	25.18
A5	High-solar-gain low-E glass	322,400	3649	4123	13.37
A6	Low-solar-gain low-E glass	310,000	19,555	22,096	2.40
A7	Window reflective film	148,800	8470	9571	2.66
A8	Movable louver shading	620,000	17,954	20,287	4.88
A9	Roller shutter shading (translucent)	372,000	11,499	12,993	4.57
A10	Roller shutter shading (opaque)	496,000	18,746	21,182	3.74
B1	Exhaust air heat recovery (standard fresh airflow)	50,000	6875	7768	0.98
B2	Exhaust air heat recovery (high fresh airflow)	80,000	10,478	11,840	1.03
C	VFD pumps	12,000	11,786	13,318	0.15
D1	Energy-efficient lamps	46,452	44,242	49,991	0.19
D2	Daylighting	70,452	113,923	128,727	0.08

Table 36 CCE for Guangzhou store building

	Technologies	Investment (RMB)	Saved cost (RMB)	Annual energy savings (kWh/year)	CCE
A1	Exterior wall 10 mm EPS	3272	1099	1242	0.40
A2	Exterior wall 20 mm EPS	8544	1725	1949	0.67
A3	Exterior wall 30 mm EPS	6816	2145	2424	0.43
A4	Roof 30 mm XPS	14,850	1719	1942	1.16
A5	High-solar-gain low-E glass	320,320	20,256	22,888	2.39
A6	Low-solar-gain low-E glass	308,000	68,011	76,849	0.69
A7	Window reflective film	147,840	19,546	22,086	1.14
A8	Movable louver shading	616,000	65,235	73,712	1.34
A9	Roller shutter shading (translucent)	369,600	44,182	49,923	1.18
A10	Roller shutter shading (opaque)	292,800	180,419	203,863	0.23
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	10,684	12,072	0.38
B2	Exhaust air heat recovery (high fresh airflow)	50,000	16,583	18,738	0.41
C	VFD pumps	10,000	4193	4738	0.36
D1	Energy-efficient lamps	34,839	7376	8334	0.83
D2	Daylighting	10,000	11,490	12,983	0.12

Table 37 NPV for Beijing office building

	Technologies	Investment (¥)	Income	PW	Calibrated PW (due to different lifetimes)
A1	Exterior wall 10 mm EPS	22,560	928	−6513	−22,560
A2	Exterior wall 20 mm EPS	15,040	621	−4302	−4302
A3	Exterior wall 30 mm EPS	22,560	928	−6513	−6513
A4	Roof 30 mm XPS	19,800	1514	6380	6380
A5	High-solar-gain low-E glass	322,400	5798	−257,936	−401,158
A6	Low-solar-gain low-E glass	310,000	14,103	−153,197	−238,262
A7	Window reflective film	148,800	2894	−116,623	−181,380
A8	Movable louver shading	620,000	18,787	−364,679	−680,586
A9	Roller shutter shading (translucent)	372,000	11,505	−215,643	−403,912
A10	Roller shutter shading (opaque)	496,000	19,607	−229,534	−457,179
B1	Exhaust air heat recovery (standard fresh airflow)	50,000	30,790	482,422	482,422
B2	Exhaust air heat recovery (high fresh airflow)	80,000	46,532	724,633	724,633
C	VFD pumps	16,000	13,227	131,063	203,837
D1	Energy-efficient lamps	46,452	46,637	331,816	599,879
D2	Daylighting	70,452	125,911	2,106,805	2,106,805

Table 38 NPV for Beijing store building

	Technologies	Investment (¥)	Income	PW	Calibrated PW (due to different lifetimes)
A1	Exterior wall 10 mm EPS	2272	350	3780	3780
A2	Exterior wall 20 mm EPS	4544	631	6367	6367
A3	Exterior wall 30 mm EPS	6816	854	7951	7951
A4	Roof 30 mm XPS	14,850	1753	15,463	15,463
A5	High-solar-gain low-E glass	320,320	29,903	12,153	18,901
A6	Low-solar-gain low-E glass	308,000	81,356	596,548	927,789
A7	Window reflective film	147,840	22,793	105,581	164,207
A8	Movable louver shading	616,000	85,703	548,732	602,188
A9	Roller shutter shading (translucent)	369,600	56,102	392,844	450,563
A10	Roller shutter shading (opaque)	492,800	90,349	735,072	897,215
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	4995	56,374	56,374
B2	Exhaust air heat recovery (high fresh airflow)	50,000	6799	67,569	67,569
C	VFD pumps	12,500	15,570	160,613	249,796
D1	Energy-efficient lamps	34,839	18,740	117,159	217,493

Table 39 NPV for Shanghai office building

	Technologies	Investment (¥)	Income	PW	Calibrated PW (due to different lifetimes)
A1	Exterior wall 10 mm EPS	7520	640	−7520	−7520
A2	Exterior wall 20 mm EPS	19,800	564	−10,047	−10,047
A3	Exterior wall 30 mm EPS	322,400	3959	−253,941	−253,941
A4	Roof 30 mm XPS	310,000	16,062	−32,255	−32,255
A5	High-solar-gain low-E glass	148,800	7990	−59,964	−93,260
A6	Low-solar-gain low-E glass	620,000	16,997	−431,021	−670,351
A7	Window reflective film	372,000	10,519	−255,046	−396,663
A8	Movable louver shading	496,000	18,147	−249,376	−485,021
A9	Roller shutter shading (translucent)	50,000	6490	38,201	39,985
A10	Roller shutter shading (opaque)	80,000	10,386	61,149	64,013
B1	Exhaust air heat recovery (standard fresh airflow)	11,000	7080	111,428	111,428
B2	Exhaust air heat recovery (high fresh airflow)	46,452	46,637	759,997	759,997
C	VFD pumps	70,452	125,911	1,329,475	2,067,686
D1	Energy-efficient lamps	46,452	46,637	331,816	599,879
D2	Daylighting	70,452	125,911	2,106,805	2,106,805

Table 40 NPV for Shanghai store building

	Technologies	Investment (¥)	Income	PW	Calibrated PW (due to different lifetimes)
A1	Exterior wall 10 mm EPS	2272	1196	18,409	18,409
A2	Exterior wall 20 mm EPS	4544	1861	27,636	27,636
A3	Exterior wall 30 mm EPS	6816	2350	33,820	33,820
A4	Roof 30 mm XPS	14,850	2901	35,314	35,314
A5	High-solar-gain low-E glass	320,320	23,149	−62,940	−97,889
A6	Low-solar-gain low-E glass	308,000	150,483	1,365,128	2,123,136
A7	Window reflective film	147,840	23,947	118,412	184,162
A8	Movable louver shading	616,000	83,551	519,485	561,150
A9	Roller shutter shading (translucent)	369,600	56,775	401,991	463,397
A10	Roller shutter shading (opaque)	492,800	87,829	700,825	849,160
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	7711	103,339	103,339
B2	Exhaust air heat recovery (high fresh airflow)	50,000	13,352	180,883	180,883
C	VFD pumps	18,000	9867	91,705	142,626
D1	Energy-efficient lamps	26,452	26,444	188,033	339,978
D2	Daylighting	44,980	11,682	157,026	157,026

Table 41 NPV for Guangzhou office building

	Technologies	Investment (¥)	Income	PW	Calibrated PW (due to different lifetimes)
A1	Exterior wall 10 mm EPS	7520	187	−7520	−7520
A2	Exterior wall 20 mm EPS	15,040	130	−12,792	−12,792
A3	Exterior wall 30 mm EPS	22,560	79	−21,194	−21,194
A4	Roof 30 mm XPS	19,800	106	−17,967	−17,967
A5	High-solar-gain low-E glass	322,400	3649	−281,829	−438,319
A6	Low-solar-gain low-E glass	310,000	19,555	−92,580	−143,986
A7	Window reflective film	148,800	8470	−54,627	−84,960
A8	Movable louver shading	620,000	17,954	−375,999	−696,471
A9	Roller shutter shading (translucent)	372,000	11,499	−215,725	−404,027
A10	Roller shutter shading (opaque)	496,000	18,746	−241,236	−473,598
B1	Exhaust air heat recovery (standard fresh airflow)	50,000	6875	68,883	68,883
B2	Exhaust air heat recovery (high fresh airflow)	80,000	10,478	101,186	101,186
C	VFD pumps	12,000	11,786	119,041	185,141
D1	Energy-efficient lamps	46,452	44,242	312,390	565,599
D2	Daylighting	70,452	113,923	1,899,508	1,899,508

Table 42 NPV for Guangzhou store building

	Technologies	Investment (¥)	Income	PW	Calibrated PW (due to different lifetimes)
A1	Exterior wall 10 mm EPS	3272	1099	−3272	−3272
A2	Exterior wall 20 mm EPS	8544	1725	21,285	21,285
A3	Exterior wall 30 mm EPS	6816	2145	30,275	30,275
A4	Roof 30 mm XPS	14,850	1719	14,875	14,875
A5	High-solar-gain low-E glass	320,320	20,256	−95,106	−147,915
A6	Low-solar-gain low-E glass	308,000	68,011	448,173	697,027
A7	Window reflective film	147,840	19,546	69,480	108,060
A8	Movable louver shading	616,000	65,235	270,565	211,868
A9	Roller shutter shading (translucent)	369,600	44,182	230,848	223,251
A10	Roller shutter shading (opaque)	292,800	180,419	2,159,153	2,949,941
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	10,684	154,748	154,748
B2	Exhaust air heat recovery (high fresh airflow)	50,000	16,583	236,754	236,754
C	VFD pumps	10,000	4193	36,619	56,953
D1	Energy-efficient lamps	34,839	7376	24,987	54,836
D2	Daylighting	10,000	11,490	188,685	188,685

Table 43 IRR for Beijing office building

	Technologies	Investment (¥)	Income	p^*
A1	Exterior wall 10 mm EPS	22,560	928	0.014142
A2	Exterior wall 20 mm EPS	15,040	621	0.014407
A3	Exterior wall 30 mm EPS	22,560	928	0.014142
A4	Roof 30 mm XPS	19,800	1514	0.064858
A5	High-solar-gain low-E glass	322,400	5798	−0.131774
A6	Low-solar-gain low-E glass	310,000	14,103	−0.044360
A7	Window reflective film	148,800	2894	−0.125212
A8	Movable louver shading	620,000	18,787	−0.101735
A9	Roller shutter shading (translucent)	372,000	11,505	−0.099269
A10	Roller shutter shading (opaque)	496,000	19,607	−0.069020
B1	Exhaust air heat recovery (standard fresh airflow)	50,000	30,790	0.615800
B2	Exhaust air heat recovery (high fresh airflow)	80,000	46,532	0.581649
C	VFD pumps	16,000	13,227	0.826589
D1	Energy-efficient lamps	46,452	46,637	1.003017
D2	Daylighting	70,452	125,911	1.787188

Table 44 IRR for Beijing store building

	Technologies	Investment (¥)	Income	p^*
A1	Exterior wall 10 mm EPS	2272	350	0.151831
A2	Exterior wall 20 mm EPS	4544	631	0.135822
A3	Exterior wall 30 mm EPS	6816	854	0.121249
A4	Roof 30 mm XPS	14,850	1753	0.113334
A5	High-solar-gain low-E glass	320,320	29,903	0.045374
A6	Low-solar-gain low-E glass	308,000	81,356	0.255435
A7	Window reflective film	147,840	22,793	0.129289
A8	Movable louver shading	616,000	85,703	0.115835
A9	Roller shutter shading (translucent)	369,600	56,102	0.132100
A10	Roller shutter shading (opaque)	492,800	90,349	0.170253
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	4995	0.164786
B2	Exhaust air heat recovery (high fresh airflow)	50,000	6799	0.132748
C	VFD pumps	12,500	15,570	1.245593
D1	Energy-efficient lamps	34,839	18,740	0.530265

Table 45 IRR for Shanghai office building

	Technologies	Investment (¥)	Income	p^*
A1	Exterior wall 10 mm EPS	7520	640	0.075527
A2	Exterior wall 20 mm EPS	19,800	564	−0.009855
A3	Exterior wall 30 mm EPS	322,400	3959	−0.055224
A4	Roof 30 mm XPS	310,000	16,062	0.031199
A5	High-solar-gain low-E glass	148,800	7990	−0.025901
A6	Low-solar-gain low-E glass	620,000	16,997	−0.094885
A7	Window reflective film	372,000	10,519	−0.092011
A8	Movable louver shading	496,000	18,147	−0.078687
A9	Roller shutter shading (translucent)	50,000	6490	0.103389
A10	Roller shutter shading (opaque)	80,000	10,386	0.103423
B1	Exhaust air heat recovery (standard fresh airflow)	11,000	7080	0.643636
B2	Exhaust air heat recovery (high fresh airflow)	46,452	46,637	1.003983
C	VFD pumps	70,452	125,911	1.787188
D1	Energy-efficient lamps	46,452	46,637	1.003017
D2	Daylighting	70,452	125,911	1.787188

Table 46 IRR for Shanghai store building

	Technologies	Investment (¥)	Income	p^*
A1	Exterior wall 10 mm EPS	2272	1196	0.526407
A2	Exterior wall 20 mm EPS	4544	1861	0.409537
A3	Exterior wall 30 mm EPS	6816	2350	0.344729
A4	Roof 30 mm XPS	14,850	2901	0.194407
A5	High-solar-gain low-E glass	320,320	23,149	0.010259
A6	Low-solar-gain low-E glass	308,000	150,483	0.487314
A7	Window reflective film	147,840	23,947	0.138980
A8	Movable louver shading	616,000	83,551	0.111225
A9	Roller shutter shading (translucent)	369,600	56,775	0.134387
A10	Roller shutter shading (opaque)	492,800	87,829	0.164254
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	7711	0.256763
B2	Exhaust air heat recovery (high fresh airflow)	50,000	13,352	0.266819
C	VFD pumps	18,000	9867	0.547382
D1	Energy-efficient lamps	26,452	26,444	0.998715
D2	Daylighting	44,980	11,682	0.259459

Table 47 IRR for Guangzhou office building

	Technologies	Investment (¥)	Income	p^*
A1	Exterior wall 10 mm EPS	7520	187	−0.017950
A2	Exterior wall 20 mm EPS	15,040	130	−0.071573
A3	Exterior wall 30 mm EPS	22,560	79	−0.109297
A4	Roof 30 mm XPS	19,800	106	−0.092231
A5	High-solar-gain low-E glass	322,400	3649	−0.168313
A6	Low-solar-gain low-E glass	310,000	19,555	−0.006833
A7	Window reflective film	148,800	8470	−0.019132
A8	Movable louver shading	620,000	17,954	−0.107179
A9	Roller shutter shading (translucent)	372,000	11,499	−0.099332
A10	Roller shutter shading (opaque)	496,000	18,746	−0.074645
B1	Exhaust air heat recovery (standard fresh airflow)	50,000	6875	0.134369
B2	Exhaust air heat recovery (high fresh airflow)	80,000	10,478	0.127386
C	VFD pumps	12,000	11,786	0.982132
D1	Energy-efficient lamps	46,452	44,242	0.951233
D2	Daylighting	70,452	113,923	1.617030

Table 48 IRR for Guangzhou store building

	Technologies	Investment (¥)	Income	p^*
A1	Exterior wall 10 mm EPS	3272	1099	0.335824
A2	Exterior wall 20 mm EPS	8544	1725	0.201068
A3	Exterior wall 30 mm EPS	6816	2145	0.314615
A4	Roof 30 mm XPS	14,850	1719	0.110810
A5	High-solar-gain low-E glass	320,320	20,256	−0.006531
A6	Low-solar-gain low-E glass	308,000	68,011	0.207812
A7	Window reflective film	147,840	19,546	0.100981
A8	Movable louver shading	616,000	65,235	0.069107
A9	Roller shutter shading (translucent)	369,600	44,182	0.089147
A10	Roller shutter shading (opaque)	292,800	180,419	0.616102
B1	Exhaust air heat recovery (standard fresh airflow)	30,000	10,684	0.356095
B2	Exhaust air heat recovery (high fresh airflow)	50,000	16,583	0.331598
C	VFD pumps	10,000	4193	0.417052
D1	Energy-efficient lamps	34,839	7376	0.168654
D2	Daylighting	10,000	11,490	1.149000

References

(2002) International Performance Measurement and Verification Protocol (IPMVP) Volume 1.

Ecofys for EURIMA (2004). Mitigation of CO2 emissions from the building stock.

Ecofys for EURIMA (2005). Cost-effective climate protection in the EU building stock of the new EU member states.

Fang, G. (2007). Master's degree thesis: Chongqing public building energy simulation and energy research. Chongqing University.

Griffith, B., Long, N., Torcellini, P., & Judkoff, R. (2007). Assessment of the technical potential for achieving net-zero energy buildings in the commercial sector[R]. Technical Report NREL/TP-550–41957.

Kneifel, J. (2010). Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. *Energy and Buildings, 42*, 333–340.

Li, Y., Pan, Y., & Chen, C. (2008). Shanghai, both office building envelope of energy-saving measures, refrigeration and air conditioning. *22*(6), 60–64.

Ma, Z., Cooper, P., Daly, D., & Ledo, L. (2012). Existing building retrofits: methodology and state-of-the-art[J]. *Energy and Buildings, 55*, 889–902.

Nikolaidis, Y., Pilavachi, P. A., & Chletsis, A. (2009). Economic evaluation of energy saving measures in a common type of Greek building. *Applied Energy, 86*, 2550–2559.

Wu, Z., & Long, W. (2008). Optimum analysis on building envelope energy efficient reform and air conditioning operating modes for public buildings in Shanghai, HVAC HV & AC *38*(3), 42–45.

Xie, Z. (1999). Shanghai public building energy consumption status and recommendations on energy saving. *Energy Saving* (11), 25–27.

Xu, P., Shen, Y., & Hua, J. S. (2012). Effectiveness of energy retrofit methods in public buildings in China; Heating Ventilating & Air Conditioning.

Jiang, Y. (2007). China's energy situation and focus on building energy consumption, construction technology 26–29.

Zhao-phase, Ren, J., & Yang, S. et al. (2008). Guangzhou office type building energy consumption and energy saving potential analysis survey. Tenth National Building Physics Conference Proceedings 74.

Xue, Z., & Jiang, Y. (2004). Beijing large public building energy situation and energy saving potential analysis, HVAC HV & AC*, 34*(9), 8–10.