

Student participants: Liu Jiarui and Hu Rishan

School: Guangzhou No. 6 Middle School

Province: Guangdong

Country/Region: China

Supervising teachers: Wu Liangyu and Huang Fengjin

Affiliation of supervising teachers: Guangzhou No. 6 Middle School

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Economic Value and Investment Thresholds of Energy Efficiency in Campus Public Buildings Based on Design Simulation Data

A Case Study of Five Public Buildings at Guangzhou No. 6 Middle School (Conghua Campus)

Abstract

Conventional life-cycle cost assessment assumes that the initial investment is known. However, early-stage assessment of energy-efficient design for campus public buildings faces two information gaps: reliable quotations for incremental costs are unavailable at project initiation, and theoretical electricity savings from design simulations may not be fully realized during operation.

This study examines Building 1# (Teaching Building), Building 3# (Canteen), Building 5# (Performing Arts Center), Building 6# (Library), and Building 8# (Senior High School Gymnasium) at Guangzhou No. 6 Middle School (Conghua Campus), hereafter referred to as the school. The inputs are the reported building floor areas and annual heating and air-conditioning energy use intensities for the design and reference buildings from the five energy efficiency design reports. The electricity price is based on a consumption-weighted average of CNY 0.62018/kWh calculated from the campus master-meter billing records for August 2025–July 2026, which are used only to estimate the electricity price, not to calibrate building-level savings.

Relative energy saving rates, theoretical electricity savings per unit area, and total theoretical electricity savings are calculated separately. A realization factor represents uncertainty in achieving the design savings, and the maximum acceptable incremental investment in energy efficiency is then calculated by setting net present value to zero. The baseline scenario assumes a 30-year evaluation period, a real discount rate of 4%, an electricity price of CNY 0.62/kWh, and a realization factor of 0.8.

Total theoretical electricity savings across the five buildings are 53,148.99 kWh/year, or 42,519.19 kWh/year after adjustment by the realization factor. The 6# Library has the highest relative energy saving rate, at 9.31%; the 1# Teaching Building has the highest total theoretical electricity savings, at 28,992.60 kWh/year, accounting for 54.55% of the total; and the 8# Senior High School Gymnasium has the highest theoretical electricity savings per unit area, at 2.59 kWh/(m²·year). The combined investment threshold in the baseline scenario is CNY 455,850.84. The 1# Teaching Building has the highest total investment threshold, at

CNY 248,700, while the 8# Senior High School Gymnasium has the highest threshold per unit area, at CNY 22.21/m².

Changes in common parameters affect threshold levels but not building rankings. With building-specific realization factors, the total-threshold ranking of the teaching building and gymnasium reverses only when $\alpha_8/\alpha_1 > 3.1801$, whereas the per-unit-area ranking of the gymnasium and library reverses when $\alpha_8/\alpha_6 < 0.8301$. Because the gymnasium's formal report and underlying ICC-ES Evaluation Service Report (ESR) file are inconsistent, the formal report is used as the primary basis and the ESR data as an alternative robustness check.

These results are conditional valuations based on design simulations and explicit scenario parameters, rather than measured operational savings or actual net returns from completed investments. The contribution is therefore an economic screening benchmark for energy efficiency investment under incomplete information, rather than a more accurate operational forecast.

Keywords: campus public buildings; simulated design energy use; life-cycle cost; investment threshold; realization factor; ranking robustness

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1 Introduction

1.1 Research Background and Problem Statement

The State Council's Action Plan for Carbon Dioxide Peaking Before 2030 identifies the green and low-carbon transition of urban and rural development and improved building energy efficiency as major tasks. It calls for stronger energy conservation reviews of fixed-asset investment projects, energy efficiency retrofits of public buildings, and more intelligent operational management ^[1]. The Implementation Plan for Carbon Peaking in Urban and Rural Development, issued by the Ministry of Housing and Urban-Rural Development and the National Development and Reform Commission, further incorporates higher building energy efficiency standards and improved public-building energy performance into its implementation pathway ^[2]. The General Code for Energy Efficiency and Renewable Energy Application in Buildings establishes unified requirements through mandatory engineering construction provisions ^[3]. Against this background, building energy efficiency concerns both engineering performance and the allocation of public funds among long-term returns, budget constraints, and uncertainty in outcomes.

A campus comprises spaces for teaching, offices, cultural and sports activities, dining, and accommodation. Buildings with different functions vary in floor area, operating hours, occupancy density, equipment loads, and environmental control requirements. Consequently, the same energy saving rate does not imply the same total electricity savings, and the same total savings do not imply the same capacity to support investment per unit area. For campus managers, knowing whether a design meets energy efficiency standards is insufficient to determine where limited funds should be allocated first.

Available project documents generally provide simulated energy use for the design and reference buildings. However, the actual incremental cost of energy efficiency may become fully clear only after detailed construction design, tendering, or final settlement. Design simulations also use standardized conditions, whereas operational performance is influenced by weather, opening hours, occupant behavior, equipment controls, and maintenance. Early-stage decisions therefore face incomplete information on both sides: verifiable incremental investment is unavailable on the cost side, while the conversion of design predictions into realized savings is uncertain on the benefit side. This study asks how existing design documents can be used, without building-level measured operational energy use or actual incremental costs, to compare energy-efficient designs for campus public buildings of different sizes and functions, estimate their conditional life-cycle economic value, and determine the maximum acceptable incremental investment in energy efficiency.

1.2 Literature Review

1.2.1 Energy Use in Campus and Public Buildings

Research on campus building energy use initially focuses on benchmarking, indicator selection, and functional heterogeneity. Dias Pereira et al. reviewed school building studies from different countries and showed that building type, educational stage, climate, and indoor environmental requirements influence energy use [4]. Khoshbakht et al. compared ordinary least squares, data envelopment analysis, and stochastic frontier analysis using 80 university buildings, demonstrating that different activity types require different energy benchmarks [5]. Gui et al. used regression analysis of weekly electricity use and space functions in subtropical university buildings, further showing that detailed use categories help explain differences between buildings [6]. For public buildings more broadly, Chung and Li et al. systematically compared statistical, engineering simulation, and data-driven benchmarking methods, emphasizing that benchmark selection must match the assessment purpose and available data [7-8].

Empirical studies of school buildings also repeatedly show that assessment results change with the scale and normalization indicator used. Ouf and Issa analyzed Canadian schools using several years of bills, weather data, and building characteristics. They found that floor area, occupancy, and building age need to be controlled, and that different energy use indicators can produce different rankings [9]. Wang developed regression prediction models for schools at different educational stages in Taiwan [10]. Daly et al., Vaisi et al., and Hong et al. examined floor area, use, climate, occupancy, and comparability using school samples from Australia, Iran, and the United Kingdom, respectively [11-13]. These studies support reporting relative efficiency, efficiency per unit area, and total contributions separately. However, they mainly address operational benchmarking or statistical explanation and depend on building-level measurements. They do not directly establish investment ceilings when actual incremental costs are unavailable at an early design stage. For existing school buildings in the hot-summer-warm-winter climate zone of southern China, retrofit measures covering the building envelope, air-conditioning, lighting, hot-water, and elevator systems have been reported to deliver an annual energy saving rate of about 20.7% [14].

1.2.2 Energy-Efficient Building Design and Reference-Building Assessment

Energy-efficient design for public buildings in China is based on mandatory codes, local standards, and performance trade-off assessment. The design documents for this case adopt *Design Standard for Energy Efficiency of Public Buildings in Guangdong Province* (DBJ 15-51-2020) for trade-off assessment. [15], within a broader technical framework that

includes the *Design Standard for Energy Efficiency of Public Buildings* (GB 50189—2015)^[16]. The reference-building approach generally maintains comparable geometric and functional conditions while setting selected envelope or system parameters to code benchmarks, then compares simulated energy use between the design and reference buildings. Foroushani, Bernhardt, and Bernhardt noted that relative results depend on how the reference building is constructed and cannot automatically replace absolute energy use indicators^[17]. Accordingly, this study calculates the energy saving rate, electricity savings per unit area, and total electricity savings separately.

Design simulation also involves software testing, traceable model evidence, and interpretation. ANSI/ASHRAE/IBPSA Standard 140 provides methods for testing building performance simulation software^[18]. Coakley et al. reviewed the main approaches to calibrating simulations against measured data^[19], while Raftery et al. proposed a calibration methodology that preserves data evidence and version records^[20]. Chong et al. further distinguished calibration, validation, and software verification, arguing that model credibility should be assessed in relation to its purpose, data, and uncertainty^[21]. Borgstein et al.'s review of energy performance assessment in non-residential buildings likewise shows that assessment, rating, benchmarking, and calibration are different concepts^[22]. These studies clarify the evidence boundary here: formal design reports can support conditional comparisons, but without building-level measured data this study cannot claim operational calibration.

1.2.3 Life-Cycle Cost and Energy Efficiency Investment Decisions

Life-cycle cost (LCC) analysis places initial investment, operating expenses, and future benefits within a common present-value framework. ISO 15686-5 specifies the basic principles of LCC analysis for buildings and constructed assets^[23]. Marszal and Heiselberg included energy efficiency levels and energy-system combinations in an LCC comparison of net-zero-energy buildings^[24]. NIST Handbook 135 systematically explains present value, evaluation periods, and sensitivity analysis for energy conservation projects^[25]. Morrissey and Horne, Ferrara et al., and Ascione et al. combined building energy simulation with life-cycle or cost-optimal analysis, showing that technology selection depends on initial costs, energy use, and assessment boundaries^[26,27-28].

Discounting formulas cannot eliminate uncertainty in economic parameters. Copiello et al. showed that discount rates substantially affect the economic assessment of retrofits^[29], and a subsequent review distinguished the decision perspectives associated with private capital costs and social discount rates^[30]. Sharbaf and Schneider-Marín reviewed cost-benefit studies

of sustainable upgrades to existing buildings, identifying net present value, payback period, and benefit-cost ratio as common indicators while emphasizing uncertainty in energy prices and discount rates ^[31]. Lee and Lee specifically examined how real discount rate estimation affects LCC accuracy ^[32]. These studies support the present-value calculations and parameter sensitivity analysis used here. However, conventional LCC analysis normally treats initial investment as a known input. Because comparable incremental costs are unknown in this case, this study solves backward at the NPV=0 boundary and defines the present value of future electricity cost savings as the maximum acceptable incremental investment, without inventing actual costs.

1.2.4 The Gap Between Simulated and Actual Operational Energy Use

De Wilde described differences between design predictions and actual measurements as the building energy performance gap and noted that these differences vary with time, environmental conditions, and observation boundaries ^[33]. Menezes et al. examined deviations between predicted and actual performance using post-occupancy assessment data for non-residential buildings ^[34]. Van Dronkelaar et al. and Zou et al. summarized the causes from non-residential building, life-cycle, and stakeholder perspectives ^[35-36]. Subsequent reviews by Cozza et al. and Zheng et al. further showed that the magnitude, causes, and solutions vary with building type, life-cycle stage, and data boundary ^[37-38]. Bell et al.'s study of commercial office buildings likewise showed that achievement of design targets requires operational assessment and cannot be established from predicted values alone ^[39].

Occupant behavior is an important source of this uncertainty. Yan et al. developed a research framework for occupant behavior in building performance simulation ^[40]. O'Brien et al. compared occupancy densities, schedules, and behavioral assumptions in codes across regions and identified substantial differences in prescribed inputs ^[41]. Chen et al. reviewed the effects of occupant presence, equipment interaction, and behavioral efficiency on building energy use ^[42]. These studies support only the general proposition that the transition from design values to operational values is uncertain; they do not provide an empirical estimate of $\alpha = 0.8$ for this case. This study therefore defines α as a transparent scenario parameter rather than a regression estimate. The value 0.8 must be reported alongside other scenarios and must not be presented as the school's measured realization level.

1.3 Data Constraints and the Research Approach

First, a gap remains between technical performance and economic limits. Many assessments stop at energy saving rates or simulated electricity savings and cannot establish how much incremental investment a project can support when its cost is unknown.

Second, a single indicator can conceal building heterogeneity. Relative energy saving rates, electricity savings per unit area, and total electricity savings depend on reference intensity, the difference per unit area, and floor area, respectively, and may yield different rankings.

Third, the evidence boundaries of simulated and measured values are not always adequately distinguished. Without building-level metering, using a campus master meter or qualitative operating schedules to validate savings in an individual building creates a mismatch in measurement scope.

The research gap addressed here is therefore how to convert design simulation data into transparent, reproducible economic decision indicators with explicit conditions under the available evidence constraints, rather than a lack of additional energy-saving technologies.

1.4 Research Questions

RQ1: Do the five public buildings have the same rankings in relative energy saving rate, theoretical electricity savings per unit area, and total theoretical electricity savings, and how does heterogeneity in size and function affect the assessment?

RQ2: Given the realization factor, discount rate, electricity price, and evaluation period, what is the life-cycle present value of theoretical electricity savings, and what are each building's total and per-unit-area investment thresholds?

RQ3: Are threshold levels and key rankings robust to changes in common parameters, building-specific realization factors, and gymnasium data versions, and where are the ranking-reversal boundaries?

1.5 Research Framework and Workflow

The study first harmonizes physical quantities, then performs economic valuation, and finally tests the boundaries of its conclusions. Source documents are organized by building, file version, and indicator name. The definitions of reported floor area, design energy use intensity, and reference energy use intensity are then aligned. Three energy performance indicators are calculated, and a realization factor converts design values into scenario-based expected values. Investment thresholds are derived from the zero-net-present-value boundary. Finally, changes in common parameters, differences in building-specific realization factors, and conflicting gymnasium file versions are examined separately. Figure 1-1 presents the workflow.

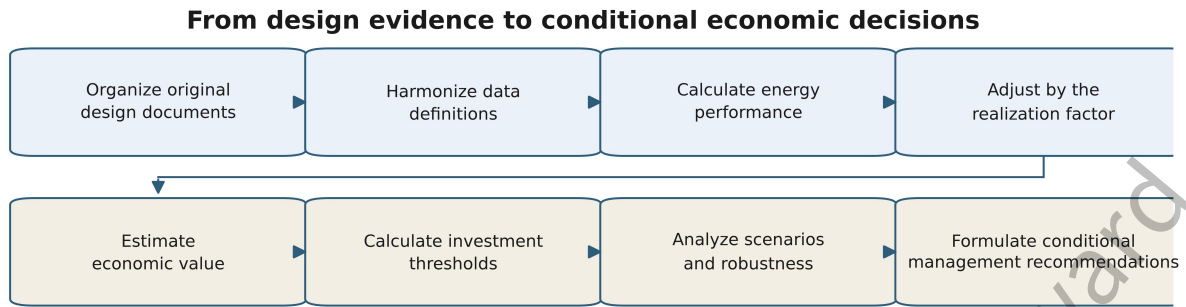


Figure 1-1 Research workflow

1.6 Research Process and Data Verification

To ensure objective input data and traceable calculations, this section documents the actual procedures for data cleaning, investigation of conflicting fields, model construction, and cross-checking.

1.6.1 Data Acquisition and Investigation of Conflicting Fields

When extracting the raw data, we identified two key field discrepancies by comparing the delivered reports with the underlying simulation outputs and established objective rules for handling them:

(1) Floor-area boundary discrepancy: The internal model areas in the underlying 'OUT' files (simulation output files) differ from the building floor areas in the formally delivered energy efficiency design reports.

(2) Energy use intensity precision discrepancy: For the 8# Senior High School Gymnasium, the formal review report gives design and reference heating and air-conditioning intensities of 40.59 and 43.18 kWh/(m² • year), respectively, whereas the underlying ESR electronic output gives 40.174335 and 43.258750 kWh/(m² • year).

We consulted Zhang Xu from the school's logistics office to clarify and trace these discrepancies. The formal review report was confirmed as the final stamped and archived deliverable. Because the underlying ESR/OUT files lacked system modification timestamps, the files alone could not rule out intermediate calculation versions or unrounded raw outputs. We therefore adopted the reported floor areas exclusively and excluded the internal OUT areas. The formal report's gymnasium intensities were entered as the primary inputs, while the ESR values were retained as a separate alternative basis for robustness testing (Section 5.4). No manual averaging or subjective exclusion was used.

1.6.2 Model Construction and Cross-Checking

The quantitative assessment was completed independently by the students, with one student constructing the model and another checking it:

(1) Main calculation workbook: Liu Jiarui constructed the underlying model in Excel. This involved entering the five buildings' raw data in matrix form, defining global scenario parameters such as the realization factor (α) and discount rate (r) in separate modules, and linking cell formulas for the net-present-value boundary and total investment thresholds strictly according to Equations (3-1) – (3-5).

(2) Formula tracing and logic review: Hu Rishan independently verified the formulas by tracing cell dependencies and checking each output against the algebraic definitions, thereby avoiding calculation errors from cross-sheet references and misplaced absolute or relative references.

1.6.3 Formula Checking and Error Correction

During model construction, the combined weighted relative energy saving rate of the five buildings was subjected to a separate checking and correction procedure.

In the first formula-tracing review, Hu Rishan found that the initial workbook had computed the weighted relative energy saving rate as the arithmetic mean of the individual rates (η_i). That treatment ignores differences in physical energy-use weights, since it assigns the same statistical weight to a large building such as the 15,340 m² 1# Teaching Building and a small building such as the 2,959 m² 6# Library in the campus aggregate; the resulting campus figure therefore did not reflect their physical characteristics.

Hu Rishan then reconstructed the aggregation logic in the main workbook on the correct physical basis. The arithmetic mean was replaced by total theoretical electricity savings divided by total simulated reference electricity use: the numerator is $\sum \Delta E_i$ for the five buildings, and the denominator is $\sum A_i e(r, i)$. The corrected weighted relative energy saving rate is 5.92% (53,148.99 / 898,412.46). This distinguishes the aggregate calculation from the individual rates and aligns the overall indicator with the underlying physical definitions. The weighted value reported in Table 4-1 is the checked result of this correction.

1.7 Research Contributions

The contributions are limited to organizing the method and applying it to this case. First, the study consistently checks design energy use data for five campus public buildings with different functions and distinguishes relative energy saving rates, efficiency per unit area, and total contributions. Second, where actual incremental costs are unavailable, it calculates the maximum acceptable incremental investment backward from NPV=0, so that the outputs can be used directly for screening once quotations become available. Third, it treats the realization factor as an explicit scenario parameter and derives ranking-reversal conditions under

heterogeneous realization factors. Fourth, where the formal report and underlying ESR file disagree for the same building, it retains both a primary and an alternative basis rather than removing the conflict through arbitrary choices. This provides a reproducible framework for other schools at an early stage with limited data, although its wider applicability requires testing with more schools and operational data.

1.8 Research Scope and Evidence Boundaries

The study covers five public buildings with available energy efficiency design documentation. It evaluates theoretical electricity savings of the design relative to the reference scheme and their conditional economic value. It does not convert theoretical electricity savings into tradable carbon credits. Recognition of carbon-credit revenue requires specific accounting methodologies, project boundaries, additionality, monitoring, reporting and verification (MRV), and trading eligibility. The available evidence is insufficient to include this potential revenue in the present cash-flow boundary. Chinese campuses have begun to explore carbon-neutrality pathways that rely partly on green-certificate and offset mechanisms ^[43], and campus-level dual-carbon studies have modeled other campus carbon flows, such as green-plant carbon sinks ^[44]; both are outside the building-energy boundary assessed here. Similarly, environmental, social, and governance (ESG) concepts may provide qualitative context for school management, but are neither endogenous variables nor an identification framework in the quantitative investment-threshold model. Buildings in the planning stage at the new campus are excluded from the empirical sample, and the conclusions are not extended to them unconditionally.

The billing records cover the campus master meter, and no formal evidence of the submeter relationships for the five buildings was obtained. They can therefore be used only to estimate the weighted average billed electricity price and describe campus electricity use. Master-meter consumption is not used to infer measured energy use in the five buildings, and qualitative information such as classroom air-conditioning schedules does not replace building-level metering. The investment threshold includes only the present value of electricity cost savings. Future incremental operation and maintenance, equipment replacement, taxes, fees, or residual value should be incorporated once supporting evidence becomes available.

2 Data Sources and Energy Performance Calculations

2.1 Case School and Building Documentation

The case data come from construction project documents for Guangzhou No. 6 Middle School (Conghua Campus). The energy efficiency design data and electricity billing records

are internal school management materials used with the school's permission; the original materials are not public. Only information directly relevant to energy comparisons and the economic model is extracted. Promotional content concerning school size, academic achievements, or building appearance is excluded. The documents cover seven buildings: the 1# Teaching Building, 2# Dormitory A, 3# Canteen, 5# Performing Arts Center, 6# Library, 8# Senior High School Gymnasium, and 16# Dormitory B. The two dormitories lack annual heating and air-conditioning design and reference intensity fields fully comparable to those of the five public buildings. They are therefore excluded from the main sample because of indicator comparability, not because they are considered unimportant.

The main sample consists of the 1# Teaching Building, 3# Canteen, 5# Performing Arts Center, 6# Library, and 8# Senior High School Gymnasium. Each formal energy efficiency design report provides the reported floor area and simulated annual heating and air-conditioning electricity use intensities for the design and reference cases, and uses DBJ 15-51 — 2020 for the trade-off assessment. Here, a comparable basis means comparability in indicator definitions, units, evaluation periods, and data levels; it does not mean that building functions, use intensities, or operating conditions are identical.

Table 2-1 Data sources, uses, and limitations

Document type	Extracted information	Use in the model	Main limitations
Building energy efficiency design reports	Reported floor areas, simulated design and reference energy use intensities	Primary energy performance calculations	Design simulations, not operational measurements
Dedicated energy efficiency sections	Energy-saving measures, system descriptions, and applicable standards	Check indicator meanings and building boundaries	Cannot replace costs or measured savings
Envelope thermal calculations	Thermal parameters of walls, roofs, doors, and windows	Check consistency of design inputs	Contributions of individual measures are not separated
Energy efficiency review forms	Code compliance and trade-off assessment results	Check compliance with design standards	Compliance does not imply economic optimality
Electrical-system energy efficiency review documents	Lighting and electrical-system descriptions	Clarify system boundaries	No operational electricity data directly attributable to the five buildings

Document type	Extracted information	Use in the model	Main limitations
Underlying ESR/OUT files	Simulation outputs and intermediate results	Alternative-data check for the gymnasium	Version differences from formal reports; OUT total electricity uses a different scope
Campus electricity billing records	Monthly electricity use and charges	Calculate the weighted average billed price	Campus master meter; cannot calibrate building-level savings

Source: Design documents and campus electricity billing records for Guangzhou No. 6 Middle School (Conghua Campus).

2.2 Main-Sample Raw Data and a Consistent Basis

The formally delivered energy efficiency design report is the primary source for each building. Floor area is the reported building floor area A_i . The energy indicator is simulated annual heating and air-conditioning electricity use intensity, with design and reference values denoted by $e(d,i)$ and $e(r,i)$, respectively, both in $\text{kWh}/(\text{m}^2 \cdot \text{year})$. This indicator does not cover all end uses in the entire building. It therefore cannot be directly added to, subtracted from, or calibrated against TOTAL ELECTRICITY in the ESR/OUT files or campus master-meter consumption.

Checks of the underlying files also identified differences between internal model areas in the OUT files and reported floor areas in the formal deliverables. The available materials do not establish whether the former represent air-conditioned calculation areas, effective areas, or other software boundaries. To align the intensity denominator with the formal report's review basis, reported floor area A_i is the only area measure used; OUT model areas are excluded from energy performance and investment-threshold calculations. This does not establish that reported area is closer to the actual area served by air conditioning. It avoids mixing spatial definitions when area boundaries are unclear. Table 2-2 presents the raw inputs.

Table 2-2 Primary inputs for the five public buildings

Building	Reported floor area A_i (m^2)	Design intensity $e(d,i)$	Reference intensity $e(r,i)$	Difference Δe_i
1# Teaching Building	15,340	29.36	31.25	1.89
3# Canteen	6,378	21.80	22.55	0.75
5# Performing Arts Center	3,477	14.66	15.78	1.12

Building	Reported floor area A_i (m ²)	Design intensity $e_{d,i}$	Reference intensity $e_{r,i}$	Difference Δe_i
6# Library	2,959	20.95	23.10	2.15
8# Senior High School Gymnasium	3,520	40.59	43.18	2.59

Note: Intensities and differences are in kWh/(m²·year). Source: Formal energy efficiency design reports for the respective buildings.

2.3 Campus Electricity Bills and the Baseline Price

The electricity-bill screenshots supplied by the school cover 14 months, from June 2025 to July 2026. Aggregating all 14 months would include two extra summer months and distort the annual pattern. We therefore select the consecutive 12 months from August 2025 to July 2026 as the full-year window. Total electricity use is 3,728,880 kWh and total charges are CNY 2,312,578.88, giving a weighted average billed price of $2,312,578.88/3,728,880 = \text{CNY } 0.620180558/\text{kWh}$. Rounded to two decimal places, $p_e=0.62 \text{ CNY/kWh}$ is the baseline proxy for the average billed electricity price.

This value is an accounting ratio of total billed charges to total electricity consumption. Basic capacity charges, time-of-use prices, and other charges are not separated. Economically, the average price need not equal the avoidable marginal price: fixed charges may not decrease proportionally with electricity savings, and heating and air-conditioning savings occur at particular times, often concentrated in specific peak or off-peak periods. Ideally, with high-frequency load data, actual electricity cost savings would be calculated over time as $\sum (\text{electricity savings}_t \times \text{avoidable price}_t)$.

Because we did not obtain electricity consumption by time period or by building, the model cannot perform this time-resolved calculation. The monetary outputs are therefore explicitly limited to conditional valuations under a proxy electricity-price scenario. The calculated present values can be interpreted as actual financial savings only when the proxy average price is numerically close to the project's true avoidable price.

The $\pm 10\%$ price sensitivity analysis in later sections is only a mechanical algebraic perturbation intended to test model elasticity. It does not establish that the interval covers actual valuation errors caused by missing tariff details, including time-of-use features and fixed charges. For a consistent economic basis, subsequent present-value calculations assume a constant real proxy price over the evaluation period and use a real discount rate. Figure 2-1 shows the 14 monthly consumption observations and the selected 12-month window; the shaded area marks the period used for price estimation.

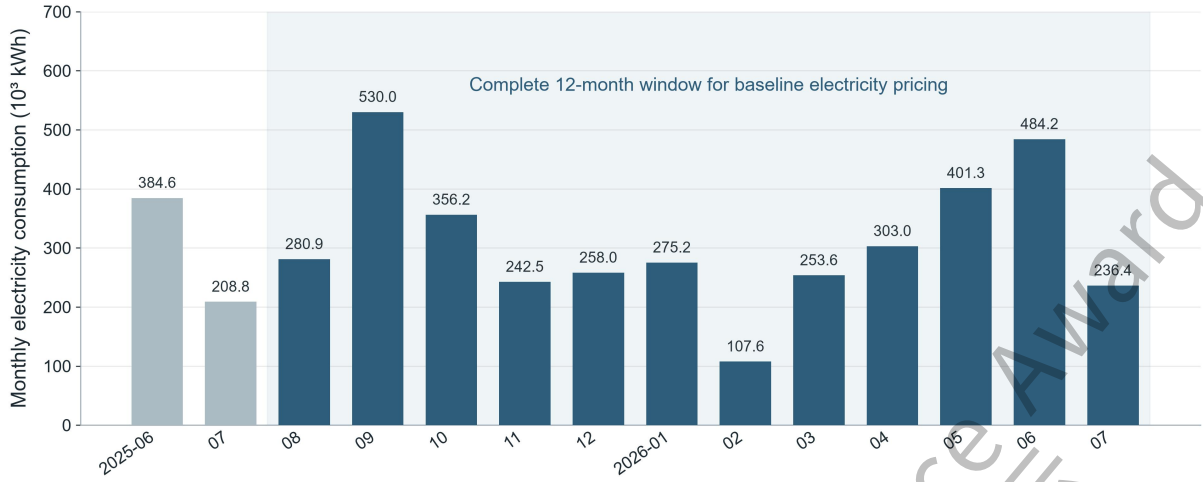


Figure 2-1 Monthly campus master-meter electricity use and the baseline price window

Source: Campus electricity billing records. Master-meter data do not represent building-level measurements for the five buildings.

2.4 Data Conflicts and Treatment Rules

Data checks found design and reference intensities of 40.59 and 43.18 kWh/(m² • year) in the 8# Senior High School Gymnasium's formal report, a difference of 2.59. The underlying ESR file gives 40.174335 and 43.258750, a difference of 3.084415. For the other four buildings, rounded ESR values broadly agree with the formal reports. The available files do not establish the specific cause of the gymnasium discrepancy, so it is not attributed to timestamps, software errors, or manual modification.

Three rules are adopted. First, the formal report is the primary basis because it is the final delivered and reviewed document. Second, ESR values are calculated separately as an alternative basis and are not averaged with the primary values. Third, OUT total electricity and model areas do not replace the reported indicators because their end-use and floor-area boundaries differ. These rules make the main results traceable while retaining a test of version uncertainty.

3 Economic Assessment Model

3.1 Energy Performance Indicators

Theoretical electricity savings per unit area, the relative energy saving rate, and total theoretical electricity savings for building i are defined as follows:

$$\Delta e_i = e_{r,i} - e_{d,i} \quad \eta_i = (e_{r,i} - e_{d,i})/e_{r,i} \times 100\% \quad \Delta E_i = \Delta e_i A_i \quad (3-1)$$

Here, Δe_i is the reference - design difference per square meter; η_i , expressed as a percentage, is this difference relative to the reference intensity; and ΔE_i combines the per-unit-area difference with building size. They answer different questions: η_i measures relative improvement, Δe_i measures the savings difference per unit area, and ΔE_i measures the total

contribution. Since the denominator of η_i is $e(r, i)$, its ranking need not match either the Δe_i or the ΔE_i ranking.

3.2 Realization Factor and the Performance Gap

Design simulations use standardized inputs, whereas operational electricity savings depend on construction quality, equipment efficiency, weather, opening hours, occupant behavior, and maintenance [33-42]. To avoid treating design values as measured values, a realization factor α_i is defined for building i , giving the expected annual electricity savings under a specified scenario:

$$S_{A,i} = \alpha_i \Delta E_i, 0 < \alpha_i \leq 1 \quad (3-2)$$

The factor α_i is neither estimated by statistical regression nor a measured assessment of any building. The restriction $0 < \alpha_i \leq 1$ in Equation (3-2) is a scenario assumption, not a physical law. Actual savings relative to the reference scheme may exceed the design difference, be zero, or even be negative. This study considers only positive realization of savings ($0 < \alpha_i \leq 1$) and assigns no occurrence probabilities to α_i . A common $\alpha = 0.8$ is used in the baseline solely to provide reproducible conditional values. Sensitivity analysis varies α from 0.6 to 1.0; this is a specified analytical range, not an empirical confidence interval. If building-level measured data become available, α_i should be re-estimated by building and year rather than treating the baseline value as a fixed technical constant.

3.3 The Net Present Value Boundary and Investment Threshold

Let C_i be the initial incremental investment in the energy-efficient scheme relative to the reference scheme, p_e the real electricity price, r the real discount rate, and N the evaluation period. Savings are assumed to accrue at each year-end, and the real electricity price is constant throughout the evaluation period. Incremental operation and maintenance, replacement, taxes, fees, subsidies, and residual value are temporarily excluded. This is a simplified present-value calculation including only electricity cost benefits, not a complete life-cycle cost assessment. N is the evaluation period chosen for this study and is not the service life of each energy-saving component. Project net present value is therefore:

$$NPV_i(C_i) = \sum_{t=1}^N [S_{A,i} p_e / (1+r)^t] - C_i \quad (3-3)$$

When $NPV_i = 0$, the initial incremental investment exactly equals the present value of future electricity cost savings. The maximum acceptable incremental investment I_i^* (investment threshold) is therefore defined as:

$$I_i^* = \alpha_i \Delta E_i p_e [1 - (1 + r)^{-N}] / r \quad C_i \leq I_i^* \quad (3-4)$$

Under these assumptions, if a future incremental investment quotation C_i on a comparable basis does not exceed I_i^* , the project's NPV within this model is non-negative. If $C_i > I_i^*$, electricity cost savings alone cannot cover the initial incremental investment. This inequality is equivalent to the model's non-negative-NPV criterion and can serve as a preliminary quotation-screening condition. However, it does not guarantee actual profitability. Real decisions require reassessment after incorporating other cash flows, including incremental operation and maintenance and equipment replacement.

3.4 Investment Threshold per Unit Area and Heterogeneity

To compare investment capacity per unit area across buildings of different sizes, define $i_i^* = I_i^* / A_i$. Substituting $\Delta E_i = A_i \Delta e_i$ cancels floor area:

$$i_i^* = I_i^* / A_i = \alpha_i \Delta e_i p_e [1 - (1 + r)^{-N}] / r \quad (3-5)$$

Equation (3-5) has two direct implications. First, with identical common parameters and realization factors α_i , the total threshold depends on $A_i \Delta e_i$, while the threshold per unit area depends only on Δe_i . Second, the relative energy saving rate η_i does not enter the threshold equation directly. The building with the highest saving rate therefore need not have the highest total or per-unit-area threshold. This reflects the indicators' different economic meanings rather than a data anomaly.

3.5 Conditional Screening under a Budget Constraint

Once comparable incremental quotations C_i and a total budget B become available, implementation for each building can be represented by a binary variable x_i . A discrete screening problem that maximizes total net present value can be written as:

$$\max \sum_i x_i (I_i^* - C_i) \quad s.t. \quad \sum_i x_i C_i \leq B, x_i \in \{0,1\} \quad (3-6)$$

In Equation (3-6), $x_i = 1$ means selecting the energy-efficient scheme for building i , and $x_i = 0$ means not selecting it. The objective maximizes the total net present value of selected projects. This is a 0-1 knapsack-type discrete optimization framework [45], in which binary variables represent the indivisibility of whole-building schemes in the current model. Selecting no projects ($x_i = 0, \forall i$) is always feasible. If a project has $C_i > I_i^*$, its contribution $I_i^* - C_i$ is negative. Removing it from any feasible solution both increases the objective and relaxes the budget constraint. Thus, no optimal solution selects such a project, and an additional constraint $x_i C_i \leq x_i I_i^*$ is unnecessary. This condition can be used to screen inputs before optimization but would be redundant within the model. If measures can be phased by equipment quantity, system, or implementation area, integer or continuous variables are

needed, together with constraints on fixed costs, capacity limits, and technical dependencies. Because comparable C_i values and an explicit budget B are unavailable, an actual optimal portfolio cannot yet be calculated. The study provides acceptable cost boundaries and the framework needed for future portfolio optimization.

3.6 Comparative Statics and Parameter Settings

Equation (3-4) shows that, other things being equal, the threshold increases with the realization factor, electricity price, and evaluation period, and decreases with the discount rate. Research on sensitivity and uncertainty in building energy analysis emphasizes explicit specification of input ranges, variable interactions, and method selection [46-49]. Given the data constraints, this study uses reproducible single-parameter and two-dimensional scenario tests and does not interpret scenario intervals as probability distributions:

$$\partial I_i^* / \partial \alpha_i > 0 \quad \partial I_i^* / \partial p_e > 0 \quad \partial I_i^* / \partial N > 0 \quad \partial I_i^* / \partial r < 0 \quad (3-7)$$

Table 3-1 Baseline scenario parameters

Parameter	Symbol	Baseline value	Evidence and explanation
Real electricity price	p_e	0.62 CNY/kWh	Rounded from the full 12-month campus master-meter average billed price of 0.62018
Realization factor	α	0.80	Research scenario assumption; not a measured estimate for this school
Real discount rate	r	4%	Research baseline assumption; not claimed to be a statutory or unique social discount rate
Evaluation period	N	30 years	Research baseline assumption; not the verified service life of each component
Incremental operation and maintenance, etc.	ΔOM	0	Temporarily excluded because data are unavailable; a limitation, not a factual finding

Note: All monetary quantities are calculated at constant prices.

4 Baseline Scenario Results

4.1 Differences in Rankings across the Three Performance Indicators

Using Table 2-2 and Equation (3-1), total theoretical electricity savings across the five buildings are 53,148.99 kWh/year. The weighted relative energy saving rate is $53,148.99/898,412.46=5.92\%$. The 6# Library has the highest relative saving rate (9.31%); the 8# Senior High School Gymnasium has the highest theoretical savings per unit area (2.59 kWh/(m² · year)); and the 1# Teaching Building has the highest total theoretical savings (28,992.60 kWh/year), accounting for 54.55% of the total. The three rankings differ substantially, as shown in Table 4-1 and Figure 4-1.

Table 4-1 Theoretical energy performance of the five buildings

Building	Relative saving rate η_i	Savings per unit area Δe_i	Theoretical savings ΔE_i (kWh/year)	Share of total
1# Teaching Building	6.05%	1.89	28,992.60	54.55%
3# Canteen	3.33%	0.75	4,783.50	9.00%
5# Performing Arts Center	7.10%	1.12	3,894.24	7.33%
6# Library	9.31%	2.15	6,361.85	11.97%
8# Senior High School Gymnasium	6.00%	2.59	9,116.80	17.15%
Total/weighted value	5.92%	—	53,148.99	100.00%

Note: Δe_i is in kWh/(m²·year). The weighted saving rate uses total simulated reference electricity use for the five buildings as its denominator.

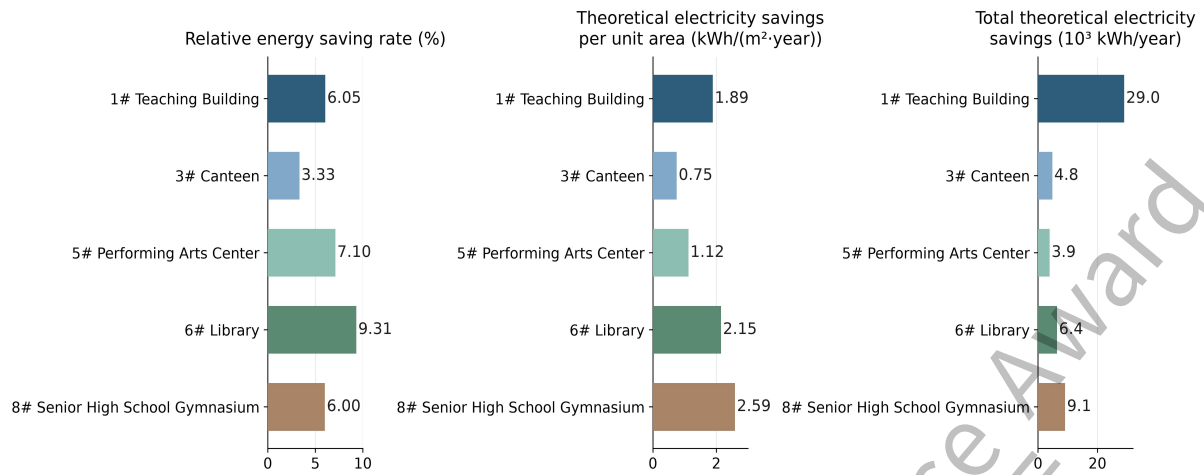


Figure 4-1 Comparison of the three energy performance indicators

Source: Formal energy efficiency design reports for the respective buildings.

The library has the highest relative saving rate but not the highest total savings because its reported floor area is only 2,959 m². The teaching building does not have the largest difference per unit area, but its 15,340 m² floor area gives it the largest total contribution. The gymnasium's advantage in the threshold per unit area comes from the largest reference - design difference Δe_i , not simply from high design energy use intensity. Ranking only by η_i places the library first; targeting the total places the teaching building first; and normalizing incremental quotations by floor area places the gymnasium first.

4.2 Life-Cycle Economic Value and Investment Thresholds

With $N=30$, $r=4\%$, $p_e=0.62$, and $\alpha=0.8$, the annuity present-value factor is 17.2920. Each 1 kWh/year of theoretical savings supports an investment threshold of CNY 8.57685. Total adjusted expected savings are 42,519.19 kWh/year. At the baseline price, their first-year electricity cost value is CNY 26,361.90, and the combined investment threshold is CNY 455,850.84. Table 4-2 presents the building-level results.

Table 4-2 Investment thresholds in the baseline scenario

Building	Adjusted savings $S_{(A,i)}$ (kWh/year)	Annual electricity cost value (CNY)	Total threshold I_i^* (CNY)	Threshold per unit area i_i^* (CNY/m ²)
1# Teaching Building	23,194.08	14,380.33	248,700	16.21
3# Canteen	3,826.80	2,372.62	41,000	6.43
5# Performing Arts Center	3,115.39	1,931.54	33,400	9.61
6# Library	5,089.48	3,155.48	54,600	18.44

Building	Adjusted savings $S_{(A,i)}$ (kWh/year)	Annual electricity cost value (CNY)	Total threshold I_i^* (CNY)	Threshold per unit area i_i^* (CNY/m ²)
8# Senior High School Gymnasium	7,293.44	4,521.93	78,200	22.21
Total	42,519.19	26,361.90	455,850.84	—

Note: Baseline parameters are listed in Table 3-1. Monetary values are calculated from unrounded data; displayed values may differ slightly because of rounding.

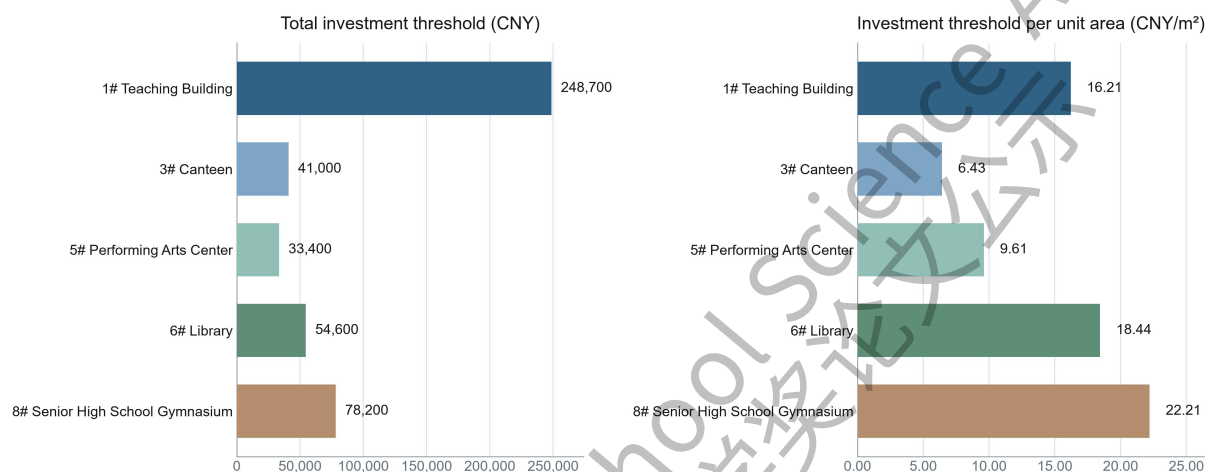


Figure 4-2 Total and per-unit-area investment thresholds in the baseline scenario

4.3 Economic Interpretation of the Results

The 1# Teaching Building's threshold of CNY 248,700 means that, under the baseline scenario and cash-flow boundary, the present value of electricity cost savings covers the comparable initial incremental investment relative to the reference scheme if that investment does not exceed this amount. It is not the market cost of the building's existing equipment or income already received by the school. Similarly, CNY 22.21/m² for the gymnasium is a critical incremental investment per unit area, not a construction unit price, and cannot establish the feasibility of any particular material or equipment.

The total and per-unit-area thresholds correspond to two decision perspectives. For an indivisible whole-building scheme, the total threshold indicates the total incremental investment the building can support. For schemes requiring unit-price comparisons across buildings, the per-unit-area threshold provides a standardized measure. Without actual quotations, the study can establish acceptable ceilings but cannot rank actual project NPVs or determine a budget-constrained portfolio.

5 Sensitivity Analysis and Robustness Checks

5.1 Effects of Common Parameters on Threshold Levels

When the five buildings share the same α , p_e , r , and N , the common parameters in Equation (3-4) form a positive multiplier for all buildings. They change threshold amounts but not total or per-unit-area rankings. This is a property of the model structure, not additional empirical validation. Table 5-1 varies the common realization factor and discount rate while holding the electricity price at CNY 0.62/kWh and the evaluation period at 30 years, and reports the combined threshold.

Table 5-1 Sensitivity to the common realization factor and discount rate (five-building total, CNY)

Common realization factor α	$r=3\%$	$r=4\%$	$r=6\%$	$r=8\%$
0.6	387,500	341,900	272,200	222,600
0.7	452,100	398,900	317,500	259,700
0.8	516,700	455,850.84	362,900	296,800
0.9	581,300	512,800	408,200	333,900
1.0	645,900	569,800	453,600	371,000

Note: These scenarios illustrate mathematical sensitivity; they are not probabilistic forecasts of future parameters.

Combined investment threshold for five buildings
under changes in common parameters (CNY)

	r = 3%	r = 4%	r = 6%	r = 8%
$\alpha = 0.6$	387,500	341,900	272,200	222,600
$\alpha = 0.7$	452,100	398,900	317,500	259,700
$\alpha = 0.8$	516,700	455,900	362,900	296,800
$\alpha = 0.9$	581,300	512,800	408,200	333,900
$\alpha = 1.0$	645,900	569,800	453,600	371,000

Electricity price: CNY 0.62/kWh; evaluation period: 30 years.

Figure 5-1 Combined investment threshold under changes in common parameters

At baseline $\alpha = 0.8$, increasing the discount rate from 3% to 8% reduces the combined threshold from CNY 516,700 to CNY 296,800. At baseline $r = 4\%$, increasing the realization factor from 0.6 to 1.0 raises it from CNY 341,900 to CNY 569,800. The threshold has unit elasticity with respect to α and the electricity price: a 10% increase in either produces a 10% increase in the threshold. With other parameters unchanged, evaluation periods of 20, 25, and 30 years give combined thresholds of CNY 358,300, CNY 411,800, and CNY 455,850.84, respectively. Mechanical price perturbations of $\pm 10\%$ around CNY 0.62/kWh give thresholds of CNY 410,300, CNY 455,850.84, and CNY 501,400. The $\pm 10\%$ interval is a sensitivity assumption, not an electricity-price forecast interval.

5.2 Building-Specific Realization Factors and Reversal of Total-Threshold

Rankings

The invariance of rankings to common parameters does not imply inherent robustness to operational differences. When α_i differs between buildings, total-threshold comparisons depend on realization-factor ratios. For the teaching building and gymnasium, cancelling the common parameters gives the following condition for the gymnasium's total threshold to exceed the teaching building's:

$$I_8^* > I_1^* \Leftrightarrow \alpha_8/\alpha_1 > \Delta E_1/\Delta E_8 = 3.1801 \quad (5-1)$$

The gymnasium's realization factor must therefore exceed 3.1801 times the teaching building's. Within the assumed range $0 < \alpha \leq 1$, if the gymnasium fully realizes its design savings ($\alpha_8 = 1$), reversal requires the teaching building's factor to fall below approximately 0.3145. If both factors are restricted to the analytical range 0.6 – 1.0, the maximum ratio is $1/0.6 = 1.6667$, so reversal cannot occur. When every building has $\alpha \in [0.6, 1]$, the teaching building's minimum scenario savings are $0.6 \times 28,992.60 = 17,395.56$, still above the largest value among the other four buildings, 9,116.80. It therefore remains first among all five, provided the floor-area basis is valid and the electricity price and present-value factor are common and positive. Under the ESR alternative, the largest competing value, 10,857.14, also remains below 17,395.56.

Thus, the teaching building's total threshold exceeding the gymnasium's is robust to building-specific realization-factor differences within this interval. This conclusion concerns this comparison and the specified interval and should not be extended to an unconditional statement covering all operating conditions.

5.3 Reversal of Per-Unit-Area Threshold Rankings

The comparison between the gymnasium and library depends on Δe and their building-specific realization factors. The gymnasium retains the higher threshold per unit area when:

$$i_8^* > i_6^* \Leftrightarrow \alpha_8 / \alpha_6 > \Delta e_6 / \Delta e_8 = 0.8301 \quad (5-2)$$

When α_8 / α_6 falls below 0.8301, the library overtakes the gymnasium. For example, if the library's realization factor is 0.9, reversal occurs when the gymnasium's factor falls below approximately 0.747. Compared with the total-threshold ranking, the gymnasium's first place per unit area is more sensitive to building-specific operational differences. Its leading position should therefore be described as holding under the common-factor baseline and nearby conditions, rather than as a fixed conclusion unaffected by operation. Figure 5-2 shows the two reversal regions.

Differences in operating conditions may affect the realization of savings, but their direction and magnitude require measured verification. Economically, 0.8301 is a critical ranking ratio, not an assessment of the two buildings' actual operation. The factor α_i aggregates operational influences that cannot be fully observed during design and can be viewed as an overall reduction in energy-saving benefits due to operational uncertainty. In theory, varying opening hours, difficulties controlling temperatures in large spaces, door and window conditions, and deviations in control strategies may reduce α_8 relative to the library's factor. The available data cannot fully establish whether the library is more stable or

how frequently these influences occur at this school and how large their effects are. Building-level metering, opening records, and equipment logs are needed to estimate α_8 / α_6 and determine whether it crosses 0.8301. Internet-of-Things temperature control could support operational monitoring, but the existing data do not establish it as a necessary investment.

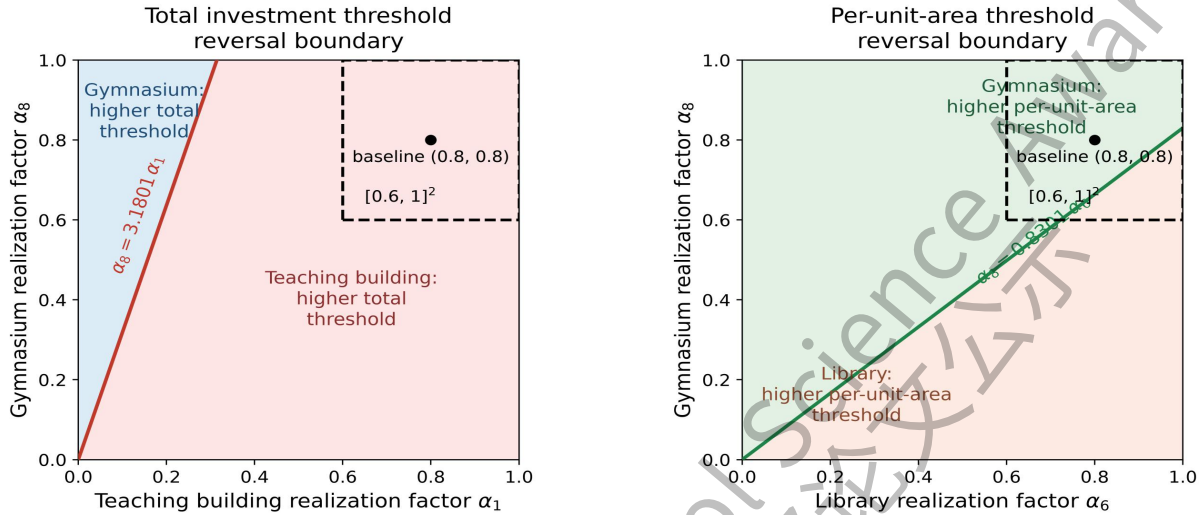


Figure 5-2 Ranking-reversal boundaries under building-specific realization factors

Note: The left panel compares total thresholds for the 1# Teaching Building and 8# Senior High School Gymnasium; the right panel compares per-unit-area thresholds for the 8# Senior High School Gymnasium and 6# Library.

5.4 Alternative Check Using the Gymnasium's ESR Data

The gymnasium's Δe is 2.59 kWh/(m² • year) on the primary basis and 3.084415 kWh/(m² • year) on the ESR basis. The alternative produces a larger savings difference; it is not a less favorable dataset. With other parameters unchanged, theoretical savings increase from 9,116.80 to 10,857.14 kWh/year, the total threshold rises from CNY 78,200 to CNY 93,120.05, and the per-unit-area threshold increases from CNY 22.21 to CNY 26.45/m². Replacing only the gymnasium data while retaining formal-report data for the other four buildings increases total theoretical savings from 53,148.99 to 54,889.33 kWh/year.

Table 5-2 Alternative check of gymnasium data versions

Indicator	Formal report (primary)	ESR (alternative)	Change
Design intensity (kWh/(m ² •year))	40.59	40.174335	-0.415665
Reference intensity (kWh/(m ² •year))	43.18	43.258750	+0.078750
Theoretical savings per unit area Δe	2.590000	3.084415	+0.494415

Indicator	Formal report (primary)	ESR (alternative)	Change
Theoretical savings ΔE (kWh/year)	9,116.80	10,857.14	+1,740.34
Total investment threshold (CNY)	78,200	93,120.05	+14,920.05
Threshold per unit area (CNY/m ²)	22.21	26.45	+4.24
Teaching building/gymnasium total-threshold reversal ratio	3.1801	2.6704	Lower boundary
Library/gymnasium per-unit-area reversal ratio	0.8301	0.6971	Lower boundary

Note: Both bases use the gymnasium's reported floor area of 3,520 m² and identical economic parameters. No cause of the version difference is inferred. Sources: Formal report and ESR file.

The alternative data do not change the teaching building's first place in total threshold or the gymnasium's first place per unit area. However, this does not mean version management can be ignored. Without version numbers, calculation times, and revision notes in formal reports and underlying files, later reviewers may struggle to identify the final design. The robustness check shows that the observed version difference does not overturn the key rankings; it does not establish that the conflict is a negligible error.

5.5 Boundaries of the Robustness Conclusions

This section distinguishes three types of uncertainty. First, common-parameter uncertainty changes all threshold levels but not rankings. Second, building-specific realization factors can change rankings: the teaching building's first place in total threshold is relatively robust, whereas the gymnasium's first place per unit area is conditional. Third, the gymnasium's file-version discrepancy does not change the key rankings in the alternative check. These are algebraic and scenario-based robustness conclusions, not statistical significance tests based on a random sample. Sensitivity analysis identifies dependence on parameter changes and does not establish measured validation of the model^[46-49]. Because the sample consists of five buildings on one campus, confidence intervals, p-values, and population-level inference are not reported.

6 Discussion: From Thresholds to Budget Decisions

6.1 Screening at Two Scales

First, the comparison scale should reflect project divisibility. For indivisible whole-building schemes, the school should compare the total threshold I_i^* with a total incremental quotation C_i on the same basis. For schemes priced per unit area with similar technical boundaries, i_i^* can also be used. A per-unit-area threshold cannot replace the overall budget constraint, and a high total threshold should not obscure a high unit cost in a large building.

Second, an eligibility condition is necessary. Only schemes whose comparable incremental quotations do not exceed the corresponding thresholds should enter subsequent portfolio selection. If quotations differ in construction scope, equipment life, or maintenance responsibilities, their cash-flow boundaries must first be aligned. The study does not recommend allocating funds simply from the highest threshold downward, since a high threshold may also reflect a larger project. Actual allocation requires C_i , budget B , and information on project divisibility.

Third, baseline and boundary values should be reported together. The teaching building can be a focus for quotation verification in total-value comparisons, but is economically acceptable only if its comparable incremental investment is below its scenario threshold. The gymnasium can be a focus for per-unit-area quotation comparisons, but its advantage is more sensitive to building-specific realization factors, requiring review of opening hours, control strategies, and maintenance conditions. Priority for checking quotations does not imply unconditional priority for construction.

6.2 Data Management and Operational Validation

The existing campus master meter provides continuous monthly consumption and average billed prices but cannot identify operating energy use for each of the five buildings. Moving from conditional valuation to actual performance validation requires, at minimum, independent building meters or verifiable circuit mappings, at least 12 months of building-level consumption, monthly opening days and major equipment operating hours, concurrent local weather data, an as-built list of energy-saving measures, and incremental costs. Estimating air-conditioning savings also requires equipment quantities, model-specific rated power, part-load ratios, temperature settings, and operating records. Daily classroom air-conditioning switch-on and switch-off times alone cannot yield reliable annual consumption.

With building-level metering, α_i can move from a scenario parameter to an estimable parameter. However, even end-use meters cannot directly identify savings or α_i . The code-

reference scheme for a new building has no actual operating readings; meters observe only electricity use after construction.

Under International Performance Measurement and Verification Protocol (IPMVP) principles, actual savings in a new project cannot be directly metered. Simulated reference energy use must therefore not simply be reduced by measured energy use under different conditions. Future verification must follow a calibrated simulation approach: first calibrate the as-built scheme using concurrent actual weather and use conditions, then construct a counterfactual reference scenario with the same boundaries to estimate the difference. Missing data and fitting errors should be reported honestly, rather than attributing simple differences in meter readings directly to the energy-efficient design.

6.3 Applicability of the Model

The model is suitable for initial economic screening at an early design stage or before costs are established, particularly when simulated design - reference energy differences are available but incremental quotations are not. It does not replace construction budgets, tender price ceilings, or actual operational assessment. The cash-flow model must be expanded when equipment life is substantially shorter than 30 years, intermediate replacement is required, or operation and maintenance costs differ. Because I_i^* in Equation (3-4) is an explicit closed-form function of α , p_e , ΔE_i , r , and N , each input can be inspected and reproduced independently, so the boundary remains transparent and auditable rather than dependent on a fitted black-box estimate.

6.4 Relationship to Previous Research

Unlike campus energy benchmarking studies, this study lacks enough building-level observations for a statistical benchmark and instead makes a structured comparison using one campus's design documents. Unlike conventional LCC analysis, it has no known initial costs and solves backward for a cost ceiling. Unlike performance-gap studies, it lacks measured data to estimate the gap and explicitly retains the realization factor as a scenario parameter. Its value therefore lies in clarifying what the available information can and cannot support and converting parameter uncertainty into calculable decision boundaries, rather than producing more accurate operational forecasts.

7 Conclusions and Limitations

7.1 Main Conclusions

(1) The five buildings rank differently across the three indicators. The library has the highest relative energy saving rate (9.31%), the gymnasium the highest theoretical savings per

unit area (2.59 kWh/(m² • year)), and the teaching building the highest total theoretical savings (28,992.60 kWh/year). These indicators represent relative improvement, the difference per unit area, and total contribution, respectively, and cannot substitute for one another.

(2) In the baseline scenario of a 30-year evaluation period, 4% real discount rate, CNY 0.62/kWh electricity price, and 0.8 realization factor, the combined investment threshold is CNY 455,850.84. The teaching building has the highest total threshold, CNY 248,700; the gymnasium has the highest per-unit-area threshold, CNY 22.21/m². These values are maximum acceptable incremental investments constrained by the present value of future electricity cost savings, not actual costs or realized returns.

(3) Changes in common parameters affect threshold levels but not rankings. Building-specific realization factors can change rankings: the gymnasium exceeds the teaching building in total threshold only if $\alpha_8/\alpha_1 > 3.1801$, and exceeds the library per unit area only if $\alpha_8/\alpha_6 > 0.8301$. The teaching building's first place in total value is therefore more robust, whereas the gymnasium's first place per unit area depends more on operational realization.

(4) The gymnasium's alternative ESR data increase rather than decrease its savings difference. Under this basis, its total threshold is CNY 93,120.05 and its per-unit-area threshold is CNY 26.45/m², with the key rankings unchanged. This version check provides some support for the main conclusions but does not fully resolve data-management issues.

7.2 Limitations and Future Validation

First, the primary data are design simulations rather than building-level operational measurements, so α cannot be estimated from this school's data.

Second, actual incremental energy efficiency costs, incremental operation and maintenance, equipment replacement, and residual values are unavailable. The outputs are therefore investment ceilings based on electricity cost benefits, not complete project net returns. Third, campus electricity bills are master-meter data and cannot establish measured rankings of the five buildings. Fourth, the sample includes only the five buildings analyzed at this school. The conclusions are based on its local climate, campus use patterns, and energy characteristics, which limit generalizability. Applying the conclusions and optimization proposals to other climates or schools of different sizes and building types requires further validation against local conditions. Fifth, the 30-year evaluation period and 4% discount rate are research assumptions that should be adjusted for the specific components and decision-makers.

Future work should prioritize building-level metering and incremental cost data rather than adding unverified parameters. Operational validation of building-level savings can follow the principles of ASHRAE Guideline 14 and IPMVP for baseline periods, reporting periods, adjustments, and measurement boundaries ^[50-51]. Only when comparable measured electricity use, operational conditions, and cost data are available can building-specific realization factors, actual net present values, and a real budget-constrained investment portfolio be determined.

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Acknowledgments

This study of the economic value of energy saving and of energy-saving planning on our campus originated in Ms. Huang Fengjin's geography class, in her careful account of "human-environment coordination", one of the four core competencies of geography. She explained that human-environment coordination is at once a core value of geography and the sound outlook that people should hold on the relationship between humanity and the geographical environment, and that human activity and development ought to proceed in harmony with that environment. When we entered Guangzhou No. 6 Middle School (Conghua Campus), we were immediately struck by a campus embraced by hills: it lies among the mountains on the outskirts of Conghua, where natural scenery and a modern campus intermingle. Prompted by Ms. Huang's teaching, we began to wonder: how has the school—nestled deep in the hills and surrounded by open country—put human-environment coordination into practice and built such a modern campus in harmony with nature? The Conghua Campus is built into the hills and has hot, rainy summers, which means that the school must consume a considerable amount of energy for cooling in order to meet the basic daily needs of its teachers and students. Energy saving is therefore not merely an engineering problem, but a question of how human-environment coordination can be realised in the everyday reality of a campus.

Under Ms. Wu Liangyu's careful guidance, we refined the basic direction of our research, and with his help we made contact with Mr. Zhang Xu of the school's Logistics Office. Mr. Zhang kindly assisted us in locating and provided key materials such as the school's energy-saving design documents, thereby laying the foundation for the subsequent research. We are especially grateful to Mr. Wu and Mr. Zhang for their generous support.

The development of this project is not only a testament to our personal growth but also a breakthrough in collective collaboration. Liu Jiarui was responsible for collating the basic data and for writing the paper; Hu Rishan was responsible for the literature search, the review of the formulas, and the revision of the English version. The research did not run smoothly and at one point stalled, particularly at the modelling stage after the data had been integrated—our knowledge of the relevant field of modelling was still insufficient, and we therefore drew on the internet and on a certain amount of artificial-intelligence assistance (DeepSeek) to learn what we needed. More importantly, our teachers gave us patient and careful guidance, and the passion we held in our hearts drew us together, so that we ultimately overcame these difficulties and moved steadily forward.

The main artificial-intelligence tool used in this project was DeepSeek, and it was employed in the following three respects: (1) methodological learning and conceptual understanding at the modelling stage, including looking up general explanations of concepts such as life-cycle cost, net present value, and investment thresholds; (2) polishing the Chinese manuscript; and (3) assisting with English expression in the English manuscript. The tool was used sporadically rather than routinely. From the initial choice of topic, through the literature search and the integration of the data, to the repeated debugging of the model and the analysis of the results, we advanced each stage step by step through exploration and trial and error, and the substantive work was carried out by our student team. Our teachers, needless to say, also helped us a great deal: Ms. Wu Liangyu carefully guided us in organising the research approach, advised us on key difficulties, and polished the logic of the exposition; Ms. Huang Fengjin exercised oversight at the level of geography's core concepts; and Ms. Tan Fei gave professional guidance on English, making the paper more consistent and rigorous in its language. All of these teachers are serving members of staff of Guangzhou No. 6 Middle School and provided their support without payment; we hereby extend our sincere gratitude to them.

The progress of this project was likewise inseparable from the strong support of the school. Grade Coordinators Pang Wei and Wang Defa gave us coordination and assistance in many respects during the research; Director Gao Yixun and Principal Wu Mali provided crucial support in sustaining the project and securing venues. During the preparation period of the project, we attended a one-week agricultural work-study programme at a labour technical school, and the teachers there specially arranged a room for us so that we could continue the project in the time outside the programme, ensuring that our research progress was not interrupted. Such consideration and support from the school were the essential backing that enabled us to persevere and complete the research.

From the ideas in the classroom, to the real drawings and data, and then to the analysis through modelling, these stages brought home to us, vividly and concretely, that human-environment coordination is not an abstract concept but a concrete action that can be measured, planned, and put into practice in every brick and tile of a campus.

The basic idea of human-environment coordination prompted us to combine theory with practice, and as the research deepened, the boundaries of each of our abilities and development were continually extended. Looking back on this valuable research experience—from the concept of human-environment coordination in the classroom to the repeated checking and re-checking between the energy-saving design documents and the electricity

ledger—we have come to understand ever more deeply what this idea means in real life. Today, as the “dual-carbon” goals have become a defining issue of our times, the green and low-carbon transformation of urban and rural development and the improvement of building energy efficiency have been written into national action plans; the energy savings of a single school may be small, yet they likewise constitute a concrete footnote to this grand process. At the same time, we came gradually to understand, in the course of the research, that the value of a paper lies not only in the conclusions it reaches but even more in clarifying what the available information can support; this caution about the boundaries of evidence is a precious gift that this research experience has bestowed on us, and an effective methodology as well. May we take this project as a starting point, continue to observe the world with a geographer’s eye and to face problems with a rigorous attitude, and contribute our own share to a green and low-carbon future.

Once again, we thank our teachers for their careful guidance, and we thank the judges for their patient review.

Supervising Teacher Profiles

Wu Liangyu is a geography teacher at Guangzhou No. 6 Middle School and an intermediate-level environmental management engineer. Wu holds a master's degree in environmental science from the Institute of Hydrobiology, Chinese Academy of Sciences, and has six years of experience in the ecological and environmental protection sector. Wu has led or participated in more than twenty projects involving environmental protection planning, ecological civilization development, circular-economy transformation of industrial parks, and energy conservation and emission reduction, and holds one granted utility model patent. During three years of teaching, Wu has received an annual award for outstanding guidance in subject competitions and currently serves as a young key teacher in science and technology education and an adviser for student innovation projects at the school.

Huang Fengjin is a member of the Communist Party of China, a senior secondary-school geography teacher, and head of the geography department at Guangzhou No. 6 Middle School. She leads a Guangzhou primary and secondary school distinguished-teacher studio and a workshop in Guangzhou's demonstration area associated with the Two Mountains concept. She is a specially appointed teaching and research adviser for senior high school geography in Guangzhou, a member of the city's primary and secondary education research core group and senior high school geography core group, and an external master's supervisor at the School of Geography, South China Normal University, and the School of Geography and Remote Sensing, Guangzhou University. Her honors include the 2024 Outstanding Teacher Who Inspires Guangzhou, Outstanding Secondary-School Geography Educator of Guangdong Province, Guangdong Key Geography Teacher, Guangzhou's Fifth Cohort of Key Primary and Secondary School Geography Teachers, selection for the fourth cohort of distinguished-teacher development under Guangzhou's Hundred - Thousand - Ten Thousand Talent Development Program, Outstanding Worker for Inland Xinjiang Senior High School Classes in Guangzhou, Outstanding Adviser for the National Earth Science Olympiad for Secondary School Students, Outstanding Adviser for the Earth Little Doctor National Geography Popularization Competition, and Outstanding Adviser for the Guangdong Primary and Secondary School Astronomy Knowledge Competition. She has taught seven graduating cohorts, whose university entrance examination results ranked among the leading groups, and received Guangzhou's Outstanding Contribution Award for the National College Entrance Examination. She has led several provincial and municipal planned research projects. Their outcomes received a first prize in Guangdong's 2025 Teaching Achievement Awards, Guangzhou Teaching Achievement Awards in 2023 and 2021, and a first prize in

Guangdong's 2020 Innovation Achievement Awards. She has published more than ten papers in core geography journals, and more than twenty teaching papers and lesson designs have received national awards. She has delivered more than twenty presentations, open lessons, and demonstration lessons at national, provincial, and municipal teaching and research events. In January 2026, she shared the practical achievements of the Phoenix Pavilion distinguished-teacher studio at the third event of the second season of Guangzhou's New Era Yangcheng Teachers Speak program. In 2019, she guided the Guangzhou No. 6 Middle School Astronomy Club in successfully naming an exoplanet, receiving an Outstanding Nomination Award from the International Astronomical Union; it was the only successful nomination by a secondary-school student club in China. She has guided and trained more than 200 students who won awards in national, provincial, and municipal competitions.

Appendix A Calculation Checks

A.1 Key Calculation Constants

Table A-1 Baseline calculation constants

Item	Calculation	Result
Annuity present-value factor	$[1-(1+0.04)^{-30}]/0.04$	17.29203330
Threshold coefficient for theoretical savings	$0.8 \times 0.62 \times 17.29203330$	8.57684852 CNY/(kWh/year)
Total theoretical savings for the five buildings	$\Sigma A_i(e_{r,i}-e_{d,i})$	53,148.99 kWh/year
Total adjusted savings	$0.8 \times 53,148.99$	42,519.192 kWh/year
Combined investment threshold	$53,148.99 \times 8.57684852$	455,850.84 CNY

Unrounded values are retained in intermediate calculations.

A.2 Check of the Gymnasium's Alternative ESR Data

The ESR difference is $43.258750 - 40.174335 = 3.084415$ kWh/(m² • year). Multiplying by the reported area of 3,520 m² gives theoretical savings of 10,857.1408 kWh/year. Multiplication by the baseline threshold coefficient, 8.57684852, gives a total threshold of CNY 93,120.05 and a per-unit-area threshold of CNY 26.45456/m². All tables are calculated from unrounded intermediate values, with rounding applied only to the final displayed values. The underlying software output contains six decimal places; this precision is retained solely to reproduce that file's calculations. It does not represent engineering measurement accuracy or replace checks of original files and versions.

Appendix B Complete 12-Month Electricity Billing Window

Table B-1 Campus electricity billing records, August 2025–July 2026

Month	Electricity use (kWh)	Electricity charges (CNY)	Average billed price (CNY/kWh)
2025-08	280,920	174,191.14	0.62007
2025-09	530,040	328,648.01	0.62004
2025-10	356,160	220,851.20	0.62009
2025-11	242,520	150,442.24	0.62033
2025-12	258,000	160,059.53	0.62039
2026-01	275,160	170,714.17	0.62042
2026-02	107,640	66,708.73	0.61974
2026-03	253,560	157,298.47	0.62036
2026-04	303,000	187,933.73	0.62024
2026-05	401,280	248,876.67	0.62021
2026-06	484,200	300,289.10	0.62018
2026-07	236,400	146,565.89	0.61999
Total/weighted average	3,728,880	2,312,578.88	0.62018

Source: Campus electricity billing records; Hu Rishan checked each month's charges divided by consumption. Monthly average prices are displayed to five decimal places; the total row uses total charges divided by total consumption.