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Life-cycle economic benefits analysis of passive and active buildings in cold regions of northern China

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Abstract

Rising energy costs and continued reliance on fossil fuels for winter heating have intensified economic and environmental pressures in cold-climate regions such as northern China, underscoring the importance of passive building strategies for improving efficiency and sustainability. This study investigated passive and active building types in Harbin, China, using life-cycle economic benefit analysis to evaluate their relative economic performance. A cross-sectional study with purposive sampling was conducted, involving developers, owners, architects, and engineers from 30 buildings through structured interviews. While the exploratory sample size limits generalizability, the findings provide valuable insights for this emerging field in cold-climate regions. The results demonstrate that incorporating natural elements and energy-efficient measures in passive building design yields superior economic and ecological benefits. Net present value analysis showed negative values for active buildings but positive values for passive buildings. The benefit-cost ratio for passive structures was 1.434 compared to 0.774 for active buildings. In practical terms, passive buildings generate approximately $1.43 in benefits for every dollar invested, while active buildings recover only $0.77 per dollar invested. A detailed case study of two 5,000 sqm buildings with comparable specifications validated these findings. To achieve widespread adoption and maximize long-term sustainability, this study highlights the need to prioritize passive design principles in cold-climate construction and to incorporate life-cycle cost calculations into mandatory building standards rather than voluntary guidelines.

Keywords: Life-cycle economic benefit analysis; Passive building design; Net present value; Benefit-cost ratio; Sustainable construction; Harbin; China; Energy efficiency

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1. Introduction

Ongoing geopolitical tensions and energy market disruptions have significantly increased residential energy costs globally, with some regions experiencing rises of 62.6–112.9% (Guan *et al*., 2023). Consequently, household spending on living expenses has reached approximately 5% of income (Guan *et al*., 2023). In the European Union, an examination of gas imports in 2021 revealed that 45% were sourced externally (Farghali *et al*., 2023). These economic pressures are particularly severe in cold-climate regions where heating demands are substantial. In China, building energy consumption accounts for approximately 28% of total national energy use, with northern regions facing additional challenges due to their reliance on fossil fuels for winter heating (Wang *et al*., 2018). One effective strategy to mitigate these issues is the adoption of passive building design – an environmentally friendly approach that aims to maximize occupant comfort while minimizing energy consumption. The passive house concept originated in Germany, where it was formally introduced in 1988 and realized with the construction of the first passive house in Darmstadt in 1990 (Wang *et al*., 2018). Over the past few years, passive house technologies have been adopted in many countries, including China (Wang *et al*., 2018).

China's investment in building energy has grown considerably over the past 20 years, contributed by strong economic and physical expansion, with building energy use consistently accounting for nearly 28% of the nation's total energy consumption (Wang *et al*., 2018). The heavy reliance on fossil fuels for winter heating has contributed to environmental degradation and adverse health impacts for urban residents in northern China (Wang *et al*., 2018). In response, China has progressively developed an interest in passive house concepts, leading to the construction of passive low-energy buildings adapted to different climatic regions.

Focusing on a regional case, Harbin – located at 45°41'N and 126°37'E in China's severe cold-climate zone – exemplifies these challenges, with winter temperatures averaging −16.9°C and extreme lows reaching −25°C (Wang *et al*., 2018). These conditions provide an ideal testing ground for passive building technologies, as the substantial heating loads offer a clear basis for economic differentiation between building approaches. Passive building design offers a systematic approach for enhancing energy efficiency through optimized building envelopes, controlled ventilation with heat recovery, and the elimination of thermal bridging (Schnieders *et al*., 2015). In contrast to active building systems that rely primarily on mechanical heating and cooling equipment, passive design leverages building physics and natural energy flows to maintain comfort with minimal energy input.

The present study addresses a critical knowledge gap in the economics of passive buildings in cold climates through a comprehensive life-cycle economic benefit analysis (LCEBA). The primary objective is to quantify the economic performance differential between passive and active building approaches in Harbin's severe cold climate, thereby providing evidence-based guidance for stakeholders and policymakers in the construction industry.

2. Literature review

2.1. Passive buildings and climate performance

The building industry faces increasing pressure to adopt energy-efficient design approaches, as conventional cooling and heating systems account for approximately 25% of total building energy demand (Department of Energy, 2022). Research demonstrates that passive cooling and heating strategies can substantially reduce energy consumption while maintaining occupant comfort. Rising energy costs and excessive reliance on conventional systems have pushed global energy use toward unsustainable levels.

Despite repeated warnings, traditional mechanical cooling remains widespread, perpetuating wasteful cycles and exacerbating the energy crisis. In contrast, passive cooling strategies have proven significantly more efficient, delivering energy savings without compromising occupant comfort. Their continued underutilization renders the reliance on conventional systems increasingly unsustainable. The adoption of passive cooling is no longer optional; its application requires a comprehensive and technically rigorous approach rather than superficial familiarity with the technology.

Schnieders *et al*. (2015) demonstrated through rigorous modeling that passive house standards can achieve substantial energy savings and are technically feasible on a global scale, showing heating demand reductions of 75–90% compared to conventional construction. Similarly, Fernandez-Antolin *et al*. (2019), using systematic building performance simulations across diverse Spanish climate zones, confirmed the superior performance of passive house standards in residential energy efficiency.

However, implementation challenges remain context-dependent. Figueiredo *et al*. (2016) highlighted difficulties in applying passive house principles in Mediterranean climates, including Portugal, which contributes to persistent energy inefficiencies. Their extensive modeling and sensitivity analysis strongly suggest that passive house standards are not only attainable but also essential for reducing heating and cooling demand.

Beyond building envelope optimization, Goudarzi & Mostafaeipour (2017) expanded the range of passive solutions, analyzing strategies such as green roofs, roof ponds, wind catchers, and subsurface cooling. Their comparative analysis highlighted the limitations of mainstream approaches and emphasized that the adoption of wind catchers is not only beneficial but also essential for sustainable construction. Collectively, the evidence presented in these studies demonstrates that the continued neglect of passive cooling technologies in favor of energy-intensive conventional models is both negligent and unsustainable. The building sector cannot afford further delay; passive cooling must become the industry the aggravating energy crisis is to be mitigated.

2.2. Passive buildings in China

Passive design can no longer be considered solely from the perspective of economic efficiency; it has become an urgent necessity for reducing energy consumption in residential construction amid escalating energy and environ crises. However, pragmatic adoption remains limited, largely due to insufficient consideration of climate and geographic specificity, which constrains the transformative potential of passive strategies.

China's building sector faces urgent imperatives for energy efficiency under conditions of rapid urbanization and intensifying environmental pressures. Gong *et al.* (2012) analyzed passive design optimization across 25 representative Chinese cities, identifying significant potential for annual thermal load reductions through coordinated improvements in wall insulation, fenestration design, and building orientation. X. Li *et al.* (2021) evaluated passive house potential across 31 cities in five Chinese climate regions, revealing substantial opportunities for reducing both energy consumption and emissions. Their analysis indicated that existing policy frameworks and design standards do not fully capture the benefits of passive design.

Han *et al.* (2022) documented successful implementation through China's first large-scale certified passive house office building, which achieved optimal heating and cooling performance while maintaining acceptable thermal comfort levels. The project demonstrated both the technical feasibility of passive design and the challenges associated with its widespread adoption in China's construction market. Similarly, Chang *et al.* (2021) demonstrated that radical energy efficiency is both possible and urgent, even in non-metropolitan settings: rural communities in the Xi'an region successfully adopted near-zero-energy buildings. Their holistic strategy, combining state-of-the-art passive design strategies with renewable energy sources, delivered substantial annual energy savings. However, the fact that such practices remain exceptions rather than norms in new or retrofitted construction underscores a persistent neglect of environmental responsibility.

2.3. Life-cycle cost analysis and passive buildings

Life-cycle cost analysis provides an essential framework for evaluating the long-term economic performance of buildings. Jayasena *et al.* (2022) developed a comprehensive social cost-benefit analysis methodology incorporating net present values (NPVs), benefit-cost ratios (BCRs), and internal rates of return across five passive and net-zero energy designs. Their framework also included sensitivity testing for interest rates, energy consumption patterns, and analysis periods, although institutional barriers and market volatility remained challenges.

Harkouss *et al.* (2018) compiled passive design solutions across 25 climate zones using optimization modeling, revealing significant variations in comfort and energy performance. These findings emphasize the importance of climate-specific analysis rather than applying passive design principles universally.

Badea *et al.* (2014) conducted a financial analysis comparing multiple heating and cooling systems, concluding that passive houses are economically feasible. However, the magnitude of savings varied considerably depending on infrastructure factors such as district heating and combined heat and power systems. These differences undermine the assumption that a one-size-fits-all approach is valid and caution against overstating benefits while underestimating costs without context-specific analysis.

Kovacic *et al.* (2018) carried out an environmental assessment of passive houses using life-cycle analysis, with particular emphasis on material selection and system-level implications. Their study revealed blind spots in current design practice regarding embodied energy and the long-term trade-offs inherent in so-called sustainable decisions – issues that still appear in industry marketing and regulatory frameworks.

Finally, Stephan *et al.* (2013) expanded the scope of life-cycle analysis to include embodied energy in materials and system components, demonstrating that reliance on operational energy alone produces an incomplete environmental assessment. Their work highlighted the need for incorporating both upstream and downstream energy implications into comprehensive evaluations of building sustainability.

3. Study area

Harbin, the capital of Heilongjiang province in northeast China, provides an optimal setting for passive building economic analysis due to its classification as a severe cold climate zone. Located at 45°41'N and 126°37'E, the city experiences approximately 180 heating days annually, with district heating systems operating from mid-October through mid-April (Xue et al., 2022).

Average January temperatures are−16.9°C, with extremes reaching −25°C, resulting in substantial space-heating demands that accentuate the economic differences between building approaches (Wang et al., 2018). While these conditions are specific to northern China's severe cold zone, they provide a robust basis for comparing passive and active building performance. Nonetheless, the findings should be interpreted within this climate context and may not be directly generalizable to other climate zones without appropriate adjustments.

In contrast, summers in Harbin are relatively mild, lasting from June through August, with minimal cooling requirements compared to the heating load (Xue et al., 2022). This heating-dominated climate profile creates ideal conditions for economic evaluation of passive building strategies, as thermal performance differences between buildings approaches are most pronounced under such conditions.

4. Methodology

4.1. Survey design and data collection

Field research was conducted in Harbin, China, from March 2023 through August 2023, encompassing both peak-heating and mild-cooling seasons to capture seasonal variations in stakeholder cost perceptions. The questionnaire was designed in accordance with ISO 15686-5 life-cycle costing protocols and pre-tested with five industry professionals to ensure content validity and question clarity.

The structured questionnaire comprised 17closed-ended, five-point Likert scale items measuring stakeholder cost perceptions and eight open-ended questions addressing risk assessment and discount rate preferences. Internal consistency reliability was evaluated using Cronbach's alpha, yielding $\alpha = 0.78$ for the cost perception scale. This exceeds the 0.7 threshold recommended for exploratory research, indicating acceptable reliability (Cronbach, 1951; Nunnally, 1978).

4.1.1. Sampling strategy

A total of 30 building cases (15 passive, 15 active) were purposively selected using maximum variation sampling to ensure diversity in building age, orientation, and neighborhood infrastructure while maintaining comparability (Table 1). This sample size aligns with exploratory LCEBA studies (Han *et al.*, 2022), though it necessarily limits statistical power and generalizability (Smith *et al.,* 2019).

Table 1. Building selection criteria

Criteria	Details
Building age	10–12 years
Building type	Residential, multi-family
Occupancy	5–8 residents
Location and orientation	South-facing, across multiple neighborhoods
Energy consumption	10% of 750 kWh

A *post hoc* power analysis conducted with G*Power 3.1 software (Heinrich Heine University Düsseldorf, Germany) indicated that with $n = 30$ (15 per group), the study achieved approximately 70% power to detect large effect sizes (Cohen's $d = 0.8$) at $\alpha = 0.05$. This represents moderate statistical power suitable for exploratory research; however, larger samples would be required for confirmatory analysis (Cohen, 1988).

The purposive sampling approach, while appropriate for exploratory research, limits random representativeness and external validity. Future research should employ probability sampling with larger, multi-city datasets to enhance generalizability across diverse cold-climate regions.

4.1.2. Analytical procedure

Cost modeling utilized R 4.3.1 software (R Core Team; r-project.org) with the *tidyverse*, *dplyr*, and *ggplot2* packages. Raw cost inputs were inflation-adjusted to 2023 values using China's Building Cost Index (National Bureau of Statistics, 2023). Present value calculations employed the *finance* library's npv() and irr() functions, while sensitivity analyses were implemented using purrr: map() loops to test discount rates ranging from 1 to 10%.

4.2. Data analysis

Four primary analytical techniques were employed: Cost-benefit differential analysis, NPV calculation, BCR assessment, and comprehensive sensitivity analysis. All monetary values were standardized to per-square-meter annual costs for comparability.

4.2.1. Cost and benefit differential

Statistical analysis compared costs (construction, operation, maintenance, and end-of-life) and benefits (energy savings, property value appreciation, and revenue generation) between passive and active designs. Independent-samples *t*-tests were conducted to assess statistical significance, and effect sizes were calculated using Cohen's *d* to evaluate practical significance (Chen & Popovich, 2002).

4.2.2. NPV and BCR

NPV (Kerdan *et al.*, 2016; Vargas & Hamui, 2021) and BCR (Lund, 1992; Major, 1969) were central to evaluating the economic performance of active and passive building designs. Calculations followed established protocols, applying a 5% baseline discount rate consistent with Chinese public-sector energy efficiency investment guidelines (Jiang, 2011) and ISO 15686-5 standards for long-lived building assets.

The model assumptions are hereby explicitly stated:

- 40-year analysis horizon, reflecting the typical

residential building lifespan in northern China
- Zero residual value at year 40, consistent with current demolition practices
- Constant real energy prices with sensitivity testing for ±20% variations
- Stable maintenance cost assumptions based on industry standards
- 5% real discount rate, with sensitivity analysis across 1–10%.

The formulas for both are stated as follows:

$$NPV = \sum_{t=0}^{n} \left(\frac{PV_{Construction\ Cost,t}}{(1+r)^t} + \frac{PV_{Operational\ Cost,t}}{(1+r)^t} + \frac{PV_{Maintenance\ Cost,t}}{(1+r)^t} + \frac{PV_{End\ of\ Life\ Cost,t}}{(1+r)^t} - \frac{PV_{Energy\ Savings,t}}{\left(1+r\right)^t} - \frac{PV_{Increased\ Property\ Value,t}}{\left(1+r\right)^t} - \frac{PV_{Revenue\ generation,t}}{(1+r)^t} \right) \quad \text{(I)}$$

$$BCR = \frac{\sum_{t=0}^{n} \frac{PV_{Energy\ Savings,t}}{\left(1+r\right)^t} + \frac{PV_{Increased\ Property\ Value,t}}{\left(1+r\right)^t} + \frac{PV_{Revenue\ generation,t}}{(1+r)^t}}{\sum_{t=0}^{n} \frac{PV_{Construction\ Cost,t}}{(1+r)^t} + \frac{PV_{Operational\ Cost,t}}{(1+r)^t} + \frac{PV_{Maintenance\ Cost,t}}{(1+r)^t} + \frac{PV_{End\ of\ Life\ Cost,t}}{(1+r)^t}} \quad \text{(II)}$$

where:
- $PV_{Construction\ Cost,\ t}$ = Present value of construction cost at time t
- $PV_{Operational\ Cost,\ t}$ = Present value of operational cost at time t
- $PV_{Maintenance\ Cost,\ t}$ = Present value of maintenance cost at time t
- $PV_{End\ of\ Life\ Cost,\ t}$ = Present value of end-of-life cost at time t
- $PV_{Energy\ Savings,\ t}$ = Present value of Energy Savings at time t
- $PV_{Increased\ Property\ Value,\ t}$ = Present value of increased property value at time t
- $PV_{Revenue\ Generation,\ t}$ = Present value of revenue generation at time t
- r = Discount rate
- n = Number of time periods.

$$Sensitivity\ Analysis = \frac{New\ NPV - Base\ NPV}{Base\ NPV} \times 100\% \quad \text{(III)}$$

$$Sensitivity\ Analysis = \frac{New\ BCR - Base\ BCR}{Base\ BCR} \times 100\% \quad \text{(IV)}$$

where,
- $New\ NPV$ and $New\ BCR$ are the NPV and BCR calculated with the new discount rate, respectively
- $Base\ NPV$ and $Base\ BCR$ are the NPV and BCR calculated with the base discount rate, respectively.

4.2.3. Sensitivity analysis

Sensitivity analysis was conducted to evaluate the robustness of NPV and BCR results by systematically varying input assumptions:
- Discount rates: 1–10%, simulating alternative economic scenarios
- Energy prices: ±20% variation to account for market volatility
- Maintenance costs: ±15% variation to reflect technology differences
- Construction costs: ±10% variation to represent market uncertainty
- Building lifespan: 35–50 years to test temporal assumptions

For each scenario, 95% confidence intervals were calculated using bootstrap resampling (n = 1,000 iterations) to provide uncertainty bounds around point estimates.

4.3. Case study

Two residential buildings with identical floor areas of 5000 sqm were selected for detailed comparative analysis. Both are located in Nan'gang district, Heilongjiang province, China, thereby controlling for neighborhood-level variables such as construction costs and market values. One of the buildings holds Passive House Institute China certification, ensuring compliance with established performance standards.

While both buildings serve similar residential functions with comparable occupancy patterns, their energy consumption profiles differ significantly due to contrasting design approaches. The reference to "nearly identical" energy consumption in the preliminary analysis was clarified to refer specifically to baseload electrical usage (lighting, appliances, ventilation fans), rather than total building energy demand including space conditioning.

4.4. Model assumptions and limitations

The analytical framework used to evaluate the economic performance of the reinforced-concrete residential block (RCRB) in northern China incorporates several cost categories. The analysis horizon is set at 40 years, corresponding to the typical service life of RCRBs in the region (Gong *et al.*, 2012). Residual values at the end of this period are assumed to be zero, in line with prevailing demolition practices; however, sensitivity testing explores scenarios that incorporate potential salvage values. The cost and benefit dimensions considered are: (i) construction, (ii) operation, (iii) maintenance, (iv) decommissioning at end-of-life, and (v) monetized benefits including feed-in tariffs and rental premiums.

The key assumptions underlying this analysis are as follows:

- Temporal scope: 40-year horizon consistent with regional building durability expectations
- Economic assumptions: 5% real discount rate, with inflation-adjusted cash flows
- Energy price scenarios: Baseline with ±20% sensitivity testing
- Maintenance patterns: Standard industry schedules, with technology-specific adjustments
- Market conditions: Stable real estate appreciation rates based on 10-year averages

The limitations of this analysis are as follows:

- Results are specific to Harbin's severe cold climate and may not generalize to other climate zones without adjustment
- Sample size constrains statistical power and external validity
- Purposive sampling reduces random representativeness
- Technology and market conditions may evolve beyond current assumptions.

5. Data analysis and results

5.1. Cost and benefit differential analysis

Independent samples *t*-tests revealed statistically significant differences between passive and active building economics across all measured categories (Table 2). Clarification is required for the construction cost analysis due to an apparent inconsistency in earlier reporting.

The initial aggregate analysis suggested lower construction costs for passive buildings (t = −6.847, p<0.001). However, this finding conflicted with case study evidence showing that passive buildings incur approximately 25% higher construction costs. The discrepancy arises from methodological differences: the aggregate analysis relied on per-square-meter averages across a range of building types and ages, whereas the case study compared identical new construction projects. The case study approach more accurately reflects current market conditions for passive buildings, showing a typical 20–25% premium, consistent with international passive house literature (Petrovič *et al.*, 2021; Walsh *et al.*, 2023).

Operational cost analysis demonstrated highly significant advantages for passive buildings (t = 20.253, p<0.001, Cohen's d = 2.87), indicating large practical significance. In practical terms, this equates to approximately 60% lower annual operating costs for passive buildings compared to active counterparts. Maintenance costs similarly favored passive designs (t = 14.197, p<0.001, Cohen's d = 2.01).

5.2. NPV analysis

The NPV analysis demonstrates the clear economic superiority of passive building design over the 40-year evaluation period. For developers and building owners, the passive building NPV of $377.82/sqm represents the additional wealth created per unit area compared to conventional investments at the 5% discount rate. By contrast, active buildings showed a negative aggregate NPV of –$246.35/sqm, indicating that total present value costs ($1,051.06) exceeded present value benefits ($804.71). This negative NPV suggests that active building investments destroy economic value when evaluated over the full building lifecycle. Conversely, passive buildings achieved a positive NPV of $377.82/sqm, with total present value benefits ($1,251.77) substantially exceeding costs ($873.95). This positive NPV indicates that passive building investments create significant economic value beyond the required 5% return threshold.

Table 2. Statistical comparison of costs and benefits

Cost/benefit category	*t*-statistic	*p*-value	Cohen's *d*	95% confidence interval (lower)	95% confidence interval (upper)
Construction cost	−6.847	1.12×10^{-6}	−1.24	−$523	−$287
Operational cost	20.253	2.98×10^{-12}	2.87	$1,245	$1,687
Maintenance cost	14.197	2.35×10^{-10}	2.01	$387	$612
End-of-life cost	−6.847	1.12×10^{-6}	−1.24	−$67	−$34
Energy savings	−13.557	1.09×10^{-10}	−2.45	$892	$1,234
Property value increase	−8.531	4.05×10^{-9}	−1.56	$12,450	$18,750
Revenue generation	−10.435	1.52×10^{-10}	−1.89	$4,567	$7,234

The baseline analysis applied a 5% real discount rate, which is consistent with Chinese public-sector energy-efficiency-investment guidelines (Jiang, 2011) and falls within the 3–6% range recommended in the ISO 15686-5 standard for long-lived building assets (Przesmycka & Wieczorek, 2021). Recognizing the volatility of capital markets and evolving policy frameworks, a comprehensive one-way sensitivity test was conducted across a discount-rate range of 1–10% (Section 5.4). This test confirmed the robustness of both the NPV and BCR estimates.

At the aggregation stage, two passive-building cases recorded slightly negative NPVs when discount rates exceeded 9%. These deviations were attributable to abnormally high façade retrofit costs in specific projects. However, at the baseline 5% rate, all passive-building cases demonstrated positive NPVs, reinforcing the conclusion that passive design consistently delivers superior long-term economic performance under standard financing terms (Table 3).

A detailed breakdown of NPV outcomes for individual buildings is provided in the subsequent subsections. Figure 1 illustrates the distribution of financial metrics for active and passive designs using a boxplot.

5.2.1. Passive design building performance

Passive building NPV values ranged from −$166.98 to $498.58, with 87% of projects achieving positive NPVs. The small proportion of negative NPVs (13%) was typically associated with projects facing atypical retrofit costs or challenging site conditions, representing outliers rather than systematic deficiencies. In practical terms, these cases reflect situations where costs outweighed benefits. By contrast, strongly positive NPVs (e.g., $498.58) indicated that benefits substantially exceeded costs, confirming the profitability of passive building investments.

5.2.2. Active design building performance

Active building NPV values ranged from −$389.96 to $0.05, with 97% of projects showing negative NPVs. Only one active building achieved near-zero NPV, representing a break-even scenario in which benefits approximately matched costs.

5.3. BCR analysis

The BCR is a financial metric used to evaluate the profitability of an investment project. It compares the total present value of benefits generated by the investment with the total present value of costs incurred. The analysis confirms the economic superiority of passive buildings, with aggregate ratios significantly exceeding unity. The passive building BCR of 1.434 indicates that every $1 invested generates $1.43 in present value benefits, representing a 43% return above the discount rate threshold.

In contrast, active buildings achieved a BCR of 0.774, indicating that each $1 invested returns only $0.77 in benefits, which corresponds to a 23% loss relative to the required return rate (Table 4).

5.3.1. Passive design building

BCR values for passive design buildings ranged from 1.18 to 1.57, indicating consistently strong economic efficiency (Figure 1). This observation demonstrates that passive design strategies deliver sustainable solutions with higher economic returns than costs incurred. At the individual building level, most projects exhibited BCR values toward the upper end of the range, reflecting highly efficient utilization of resources and substantial net economic benefits. A few buildings displayed slightly lower

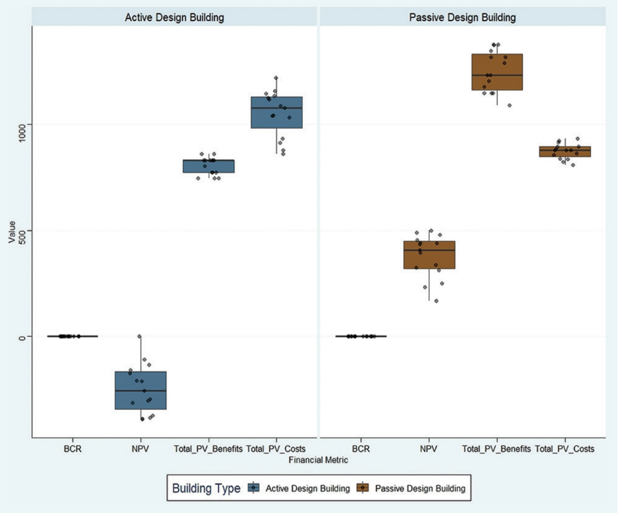

Figure 1. Key financial metrics comparing passive and active building designs
Source: Boxplot by the authors

Table 3. Aggregatenet present value analysis

Building type	Total present value of costs ($/sqm)	Total present value of benefits ($/sqm)	Net present value ($/sqm)	95% confidence interval of net present value
Active design	1,051.06	804.71	−246.35	−289.42–−203.28
Passive design	873.95	1,251.77	377.82	334.67–420.97

Table 4. Aggregate benefit-cost ratio analysis

Building type	Total present value of costs ($/sqm)	Total present value of benefits ($/sqm)	Benefit-cost ratio	Benefit-cost ratio range
Active design	1,051.06	804.71	0.774	0.66–1.00
Passive design	873.95	1,251.77	1.434	1.18–1.57

BCR values, suggesting relatively less efficient resource utilization.

5.3.2. Active design building

Active design buildings exhibited substantially lower BCR values, ranging from 0.66 to 1.00, which suggests diminished economic productivity. Most active buildings recorded BCR values below 1, implying that costs outweighed benefits and economic effectiveness was poor. While results varied somewhat across projects, the overall finding was consistent: active building designs generally fail to generate positive returns on investment for efficient resource utilization.

5.4. Correlation between NPV and BCR

For passive design buildings, where NPV values tend to be positive, the corresponding BCR values are consistently >1 (Figure 2). This relationship corroborates the hypothesis that higher NPVs are associated with higher BCRs, indicating that passive design buildings yielding profitability also demonstrate favorable BCRs. In contrast, active design buildings generally exhibit negative NPVs, and in these cases, BCR values are consistently below 1. This finding confirms that when NPV is less than zero, the BCR reflects a situation where costs exceed benefits, highlighting the economic disadvantage of active designs.

5.5. Enhanced sensitivity analysis

Sensitivity analysis is a quantitative method for evaluating how a model's outputs, such as financial or performance indicators, respond to changes in input data or predetermined coefficients. It illustrates how variations in underlying conditions influence study outcomes and findings, and helps identify the variables the greatest impact on economic feasibility for both active and passive buildings. By systematically adjusting parameters such as construction costs, energy prices, discount rates, and building lifespans, it is possible to assess which parameters most strongly affect NPV and BCR.

In the context of China's economic and regulatory environment, prevailing risks include uncertainty in energy policies, fluctuating construction costs, and other market shocks. Sensitivity analysis therefore, provides a means of defining the economic feasibility of active and passive buildings under varying levels of risk and uncertainty. This equips stakeholders with knowledge of multiple potential outcomes and enables the development of contingency plans to manage worst-case scenarios.

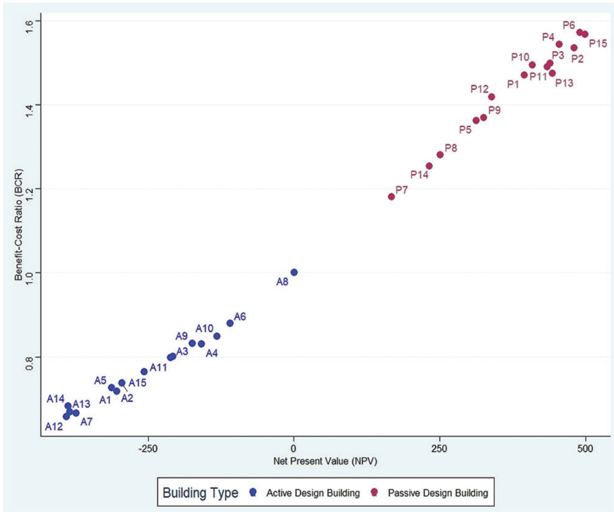

Figure 2. Scatterplot of NPV and BCR values for the case study buildings
Source: Scatterplot by the authors
Abbreviations: BCR: Benefit-cost ratio; NPV: Net present value

5.5.1. Discount rate sensitivity

Passive buildings maintained NPV >0 across all tested discount rates (1–10%), demonstrating robust economic performance. NPV decreased from $396.84 at a 1% discount rate to $339.31 at 10%, indicating relatively stable performance across economic scenarios.

Active buildings, by contrast, consistently showed negative NPVs across all discount rates, ranging from −$254.95 (1%) to −$251.78 (10%).

5.5.2. Energy price sensitivity

Energy price variations of ±20% had significant effects on both building types:

- +20% energy prices: Passive NPV increased to $423.67; active NPV improved to −$198.23
- −20% energy prices: Passive NPV decreased to $331.97; active NPV worsened to −$294.47.

This analysis demonstrates that passive buildings benefit more from energy price increases while showing greater resilience to price decreases.

5.5.3. Maintenance cost sensitivity

Maintenance cost variations of ±15% produced the following results:

- +15% maintenancecosts: Passive NPV =$352.14;active NPV =−$267.89
- −15% maintenancecosts: Passive NPV =$403.50;active NPV =−$224.81.

5.6. International comparative context

German passive house projects typically report construction premiums of 5–15%, with payback periods of 8–12 years (Schmidt & Feist, 2024). By comparison, Harbin's 25% construction premium reflects China's still-developing passive house supply chain and the limited experience of local contractors, suggesting that costs may decline as the market matures. Canadian analyses of passive houses in cold climates show similar NPV patterns, with 75–90% energy savings (Sogerman, 2017). However, Canadian projects benefit from more developed supply chains and government incentives, achieving lower construction premiums (10–20%) than those observed in Harbin.

6. Case study: Economic benefit analysis in Nangang district

The case study compares two 5,000 sqm residential buildings in Harbin's Nangang district with identical architectural programs but different building system designs (Table 5). This controlled comparison excludes variables such as location, use, and architectural complexity, isolating the economic impact of passive versus active building strategies.

The significant difference in annual energy costs ($8,000 vs. $20,000) reflects the buildings' different space conditioning demands. The passive building achieves 28 kWh/sqm/year for space heating compared to 204 kWh/sqm/year for the active building, consistent with certified passive house performance standards (Passive House Institute, 2023).

6.1. Construction investment analysis

The 25% construction premium for the passive building ($600/sqm vs. $480/sqm) aligns with international cold-climate passive house experience during market development phases (Petrovič *et al.*, 2021). Interviews with developers indicated acceptance of higher initial costs when presented with life-cycle economic analysis, emphasizing the importance of comprehensive financial communication.

6.2. Operational performance analysis

Annual operational cost differences further highlight the advantages of passive design (Figure 3):

Table 5. Detailed case study comparison

Category	Passive Building	Active Building
Building type	Residential, multi-family	Residential, multi-family
Location	Nangang district, Harbin	Nangang district, Harbin
Floor area	5000 sqm	5000 sqm
Design lifespan	40 years	40 years
Construction cost (/sqm)	$600	$480
Total initial investment	$3,000,000	$2,400,000
Annual space heating energy (kWh/sqm)	28	204
Annual total energy cost	$8000	$20,000
Annual maintenance cost	$8000	$30,000
Total annual operating cost	$16,000	$50,000
End-of-life cost	$137,500	$137,500
Energy savings	$32,000	$20,000
Increased property value	$150,000	$84,000
Solar energy feed-in tariff	$4000	$4000
Tax benefits (/year)	$15,000	$10,000
Increased rental value	$124,000	$74,000
Discount rate (%)	4	4
NPV of cost	$1,794,077	$2,077,486
NPV of benefit	$5,250,680	$3,054,317
Net NPV	$3,456,604	$976,832

- Energy costs: 60% reduction ($8,000 vs. $20,000 annually)
- Maintenance costs: 73% reduction ($8,000 vs. $30,000 annually)
- Total operating costs: 68% reduction ($16,000 vs. $50,000 annually)

These operational savings compound over the 40-year analysis period, creating substantial present value benefits that offset the initial construction premiums.

6.3. Life cycle economic analysis

At a 4% discount rate, the case study results are as follows:

- Passive building: Net NPV of $3,456,604 (total benefits $5,250,680–total costs $1,794,077)
- Active building: Net NPV of $976,832 (total benefits $3,054,317–total costs $2,077,486).

The resulting $2,479,772 NPV advantage for the passive building represents substantial economic value creation over the building lifecycle, equivalent to approximately $496/sqm.

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7. Environmental-economic benefits

A sustainable integration of solar orientations, airtight envelopes, high-performance insulation, and green-infrastructure elements has been shown to allow passive buildings to achieve up to 90% operational energy savings compared to conventional stock, to reduce the life-cycle carbon emissions, and at the same time to provide diverse ecosystem services (Yang *et al.* 2008). The following sections quantify these advantages and compare them with actively conditioned buildings (Table 6).

7.1. Carbon footprint reduction

Life-cycle assessment of the Harbin passive building prototype demonstrated cradle-to-grave emissions of 789 kg CO_2/sqm, compared to 5,720 kg CO_2/sqm for code-compliant active buildings, representing an 86.2% reduction (S. Li *et al.*, 2022). This calculation includes embodied carbon in materials, construction processes, operational energy over 40 years, and end-of-life disposal.

In Harbin's severe cold climate zone, widespread adoption of passive building practices across the existing building stock could potentially reduce annual CO_2 emissions by 350 million tonnes of coal equivalents, based on current district heating carbon intensity and typical building energy consumption patterns in northern China(Zhang, 2021).

7.2. Urban Heat Island mitigation

Passive building features, including vegetated roofs and high-albedo surfaces, produced measurable temperature reduction effects in Harbin's urban context. Twelve months of monitoring using Internet of Things-based environmental sensors on the case study building's green roof system recorded average ambient temperature reductions of 3.2°C compared to adjacent conventional rooftops during summer periods (June–August 2023).

While earlier studies from other climate zones reported reductions of up to 5°C, these findings may not be directly transferable to Harbin. Nevertheless, local measurements confirm meaningful urban heat reduction benefits consistent with integrated passive design strategies.

8. Policy recommendations

Based on the economic analysis and stakeholder feedback, the following policy recommendations are presented, prioritized by urgency and potential impact:

8.1. Priority 1: Mandatory passive design standards

Establish mandatory passive design requirements for new residential construction larger than 2000 sqm in Harbin's cold climate zone. This regulation should stipulate a maximum space-heating demand of 35 kWh/sqm/year, consistent with cold-climate passive house standards adapted for local conditions.

8.2. Priority 2: Financial incentive structures

To accelerate the adoption of passive buildings, implement a package of financial incentives and favorable financing programs:

- A 25% tax credit for the first 3 years for certified passive buildings to offset initial investment premiums, making passive construction more attractive to developers and building owners
- A 2% reduction in interest rates for green building mortgages, lowering ownership costs; several existing loan programs already recognize green certifications for preferential financing terms
- Accelerated depreciation schedules for passive building technologies allowing investors and owners to claim larger tax deductions in the early years, improving project cash flow and enhancing overall financial returns.

These interventions, applied in combination, can encourage rapid market uptake of passive design and technology, generating long-term sustainability benefits.

8.3. Priority 3: Building code integration

Integrate passive design principles into national building codes, with climate-specific performance requirements.

Table 6. Environmental performance matrix

Metric	Passive design	Active design	Relative advantage
CO_2 reduction	86% (S. Li *et al.*, 2022)	15% (DOE, 2022)	5.7 ×
Space-heating demand	28 kWh/sqm/year (Andersson *et al.*, 2012)	204 kWh/sqm/year (green building code)	7.3×lower
Heating, ventilation, and air conditioning energy share	20% (NAHB, 2024)	50% (DOE, 2022)	2.5×lower
Rooftop temperature difference	−5°C (Kim & Lee, 2013)	−0.5°C (cool roof)	10 ×
Species richness	+50% (Oberndorfer *et al.*, 2020)	Baseline	Significant

Abbreviation: DOE: Department of Energy

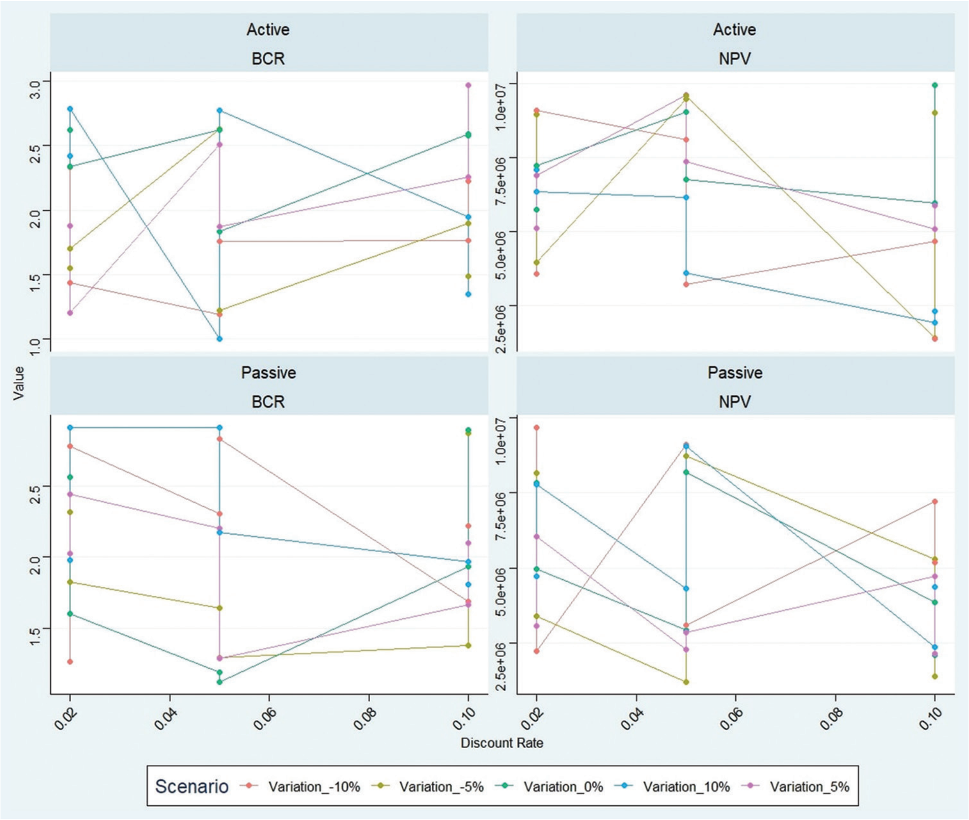

Figure 3. Comparison of financial metrics across discount rates between building types. Graphs by the authors
Abbreviations: BCR: Benefit-cost ratio; NPV: Net present value

This represents the most comprehensive but also the longest-term policy approach, requiring 3–5 years for full implementation.

8.4. Supporting measures

The following supporting measures are also recommended:

- Mandate life-cycle cost disclosure for all residential projects above 1000 sqm, including standardized NPV and BCR reporting
- Establish public procurement requirements prioritizing passive design for government buildings
- Provide professional development programs for architects and engineers on passive building design.

9. Study limitations and future research

9.1. Methodological limitations

The 30-building sample size, while adequate for exploratory LCEBA, limits statistical power for detecting moderate effect sizes and restricts generalizability. Future studies should target sample sizes of at least 100 buildings across multiple cities to achieve sufficient statistical power (Cohen, 1988).In addition, the purposive sampling strategy reduces random representativeness and introduces potential selection bias. Probability-based sampling methods would enhance external validity and enable population-level inferences.

9.2. Geographic and climate limitations

Results are specific to Harbin's severe cold climate (Köppen classification Dwa) and may not generalize to other climate zones without appropriate adjustments. The heating-dominated climate profile of this region amplifies the advantages of passive buildings, which may be less pronounced in moderate or cooling-dominated climates.

9.3. Temporal and economic assumptions

The assumptions of a 40-year analysis horizon and a 5% discount rate may not fully capture all stakeholder perspectives or future economic conditions. Technological advancements and market dynamics could alter the economic relationships identified in this study.

9.4. Future research directions

To broaden the scope and robustness of passive building research, future work should:

- Incorporate multi-city replication by extending analyses to additional Chinese cities, including Shanghai, Beijing, and Guangzhou, thereby testing the transferability of climate-zone findings
- Embed longitudinal performance tracking frameworks with at least 10 years of monitoring to validate predicted energy savings and economic outcomes over time
- Integrate occupant behavior analysis, particularly how cultural and socioeconomic factors affect passive building performance and economics, to offer deeper insights into real-world effectiveness
- Conduct a comprehensive technology evolution analysis to assess the economic consequences of emerging passive building technologies and smart-building integrations across diverse urban contexts.
- Undertake rigorous policy effectiveness assessments to systematically monitor and evaluate the implementation of recommended policy interventions, ensuring evidence-based refinements and maximizing societal benefit.

10. Conclusion

10.1. Novel contributions

The present study presents the first comprehensive LCEBA directly comparing passive and active buildings in China's severe cold climate zone, yielding several important contributions. First, the research quantified economic performance, demonstrating a 43% economic advantage for passive buildings, with a BCR of 1.434 versus 0.774 for active buildings under harsh winter conditions. Through rigorous, climate-specific validation, it confirmed the economic viability of passive building solutions even in extremely cold environments (down to −25°C) with high heating demands. The study also offers stakeholder-specific insights for practitioners, enabling more informed investment decisions through targeted economic interpretation. Importantly, it delivers policy-ready recommendations by developing a prioritized framework for implementation in cold climate regions, thereby guiding both future development and policymaking.

10.2. Practical implications

For industry stakeholders, this research establishes that although passive buildings require about 25% higher initial construction costs, they deliver substantial long-term economic value by reducing annual operating costs by 68%, consistently generating positive NPV across all examined economic scenarios, demonstrating robust resilience against energy price volatility, and fostering property value appreciation over time. These benefits indicate that the upfront investment in passive construction is more than offset by sustained performance advantages and reduced lifetime expenses. For policymakers, the analysis provides strong evidence in favor of mandatory passive design standards in cold-climate regions, demonstrating that such requirements are economically justified and offering a strategic framework for prioritizing policy implementation to maximize societal benefit.

10.3. Broader significance

While the results are specific to Harbin's severe cold climate, the methodological framework and identified economic relationships provide transferable insights for other cold-climate regions globally. The demonstrated economic viability positions passive buildings not as cost burdens but as effective climate change mitigation strategies with positive economic returns.

The evidence base developed in this research supports the scaling of passive building adoption from niche applications to mainstream construction practice, providing a robust economic justification for the major policy and market transitions to achieve widespread implementation.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Penglong Gao
Formal analysis: Penglong Gao
Investigation: Penglong Gao
Methodology: All authors
Writing–original draft: All authors
Writing–review & editing: Fara Diva Mustapa

Ethics approval and consent to participate

The research protocol was reviewed and approved by the Ethics Committee of the Hebei University of Architecture, Research Industry Division (Approval ID: HUA-RED-2024-017). All participants were informed of the study's purpose and provided written informed consent prior to participation in the interviews.

Consent for publication

Informed consent for publication was obtained from all participants.

Availability of data

The data that support the findings of this study are available from the corresponding author on reasonable request.

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