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Energy Saving Potential and Economic Optimization of Ground-Floor Insulation (Case Study of Samarkand Climate)

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Abstract

This study evaluates the energy-saving potential and economically optimal thickness of ground-floor insulation for the climate of Samarkand. Calculations were performed using the zonal method for a reference 12×10 m (120 m²) single-story building without a basement, based on design thermal conductivity (λ) values for mineral wool and glass fiber from the 2024 amendments to ShNQ 2.01.04-2018, reference values for XPS, EPS, PUR, PIR, and foam glass, and energy tariffs effective from June 1, 2026. Uninsulated floor annual heat loss was determined at 20.5 kWh/m² (approx. 2,460 kWh/year); a 50 mm insulation layer reduces heat loss by 24.3–47.7%. Payback depends heavily on energy type: under electric heating, simple payback ranges from 1.7 to 8.2 years (20.8 years for foam glass), whereas under residential natural gas tariffs (1,100 UZS/m³), payback exceeds 20 years. Under electric heating, economically optimal thickness is approximately 90 mm for EPS, 40 mm for XPS and dense mineral wool, and does not exceed 20–30 mm for PIR and PUR. Perimeter (Zone I) insulation yields 1.4 times higher energy savings per m². Material prices represent a conditional scenario and should be refined with actual commercial quotes.

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INTRODUCTION

Heat loss through ground-connected first-floor slabs is highest along external walls; thus, increasing the thermal resistance of zones near the perimeter is a key direction for energy efficiency. The amendments introduced to ShNQ 2.01.04-2018 by Order No. 01/2-5 dated March 26, 2024, established updated design

thermal conductivity values by density for mineral wool and glass fiber products. In a previous work by the author, these values were compared with cellular polymers regarding thermal-physical indicators. However, material selection depends not only on thermal conductivity (λ), but also on energy price, material cost, and insulation layer thickness. As thickness increases, incremental energy savings diminish while material cost grows linearly, establishing an economically optimal thickness [1].

The aim of the study is to determine the energy-saving potential of ground-floor insulation for the climate of Samarkand, and to evaluate the simple payback period and economically optimal thickness across various insulation materials.

Specific research tasks include [2]:

1. Calculate annual heat loss of an uninsulated floor using the zonal method and heating degree-days (HDD);
2. Evaluate energy and monetary savings for a 50 mm insulation layer under natural gas and electricity tariffs;
3. Determine simple payback period and life-cycle costs to identify optimal insulation thickness;
4. Establish a price-independent criterion—the maximum allowable material cost per unit area;
5. Compare full floor insulation with perimeter-only (Zone I) insulation [3].

METHODOLOGY

Calculations were conducted for a reference single-story building measuring 12×10 m (120 m² floor area in plan), without a basement, with a concrete slab placed directly on ground. In accordance with standard zonal methodology, zones were designated starting from external walls inward in 2 m wide bands: Zone I = 72 m², Zone II = 40 m², Zone III = 8 m². Initial thermal resistances of uninsulated zones were taken as R_1^0 = 2.1 m²·°C/W, R_2^0 = 4.3 m²·°C/W, and R_3^0 = 8.6 m²·°C/W.

Thermal resistance of insulated zones (R_i), annual energy consumption (E), and annual saved energy (ΔE) were determined using Equations 1–3:

$$R_i = R_i^0 + \delta / \lambda \quad (1)$$

$$E = (24 \cdot Dd / 1000) \cdot \Sigma (A_i / R_i) \quad (2)$$

$$\Delta E = E_0 - E(\delta) \quad (3)$$

where δ is insulation thickness (m), λ is design thermal conductivity (W/m·°C), Dd is heating degree-days (°C·days), A_i is zone area (m²), E is annual heat loss (kWh/year), and E_0 is baseline annual heat loss without insulation.

For economic evaluations, simple payback period (T_ok), life-cycle cost (LCC), and analytical optimal thickness (δ_opt) were calculated using Equations 4–6:

$$T_ok = c_v \cdot \delta / (p \cdot \Delta E) \quad (4)$$

$$LCC(\delta) = c_v \cdot \delta + p \cdot E(\delta) \cdot PVF, \quad PVF = [1 - (1 + r)^{-N}] / r \quad (5)$$

$$\delta_opt = \sqrt{(K \cdot \lambda / c_v)} - \lambda \cdot R^0, \quad K = 0.024 \cdot Dd \cdot p \cdot PVF \quad (6)$$

where c_v is volumetric material cost (UZS/m³), p is the unit cost of thermal energy (UZS/kWh), r is discount rate (15%), and N is economic analysis period (20 years, yielding PVF = 6.26). Economic benefit is measured by LCC reduction relative to the uninsulated baseline; negative values indicate that insulation is economically unjustified under given parameters. Calculations were performed under steady-state conditions.

Baseline parameters and conditional material unit costs used in calculations are presented in Tables 1 and 2.

Table 1. Initial Input Data for Calculations

Parameter	Value	Source / Remark
Building & zones	12×10 m; A_I = 72, A_II = 40, A_III = 8 m²	Conditional reference model
Uninsulated zone resistance, m²·°C/W	2.1; 4.3; 8.6	Reference literature
Heating degree-days Dd, °C·days	2,300 (sensitivity 2,000–2,600)	Estimated for Samarkand (±13%)
λ, W/(m·°C): Mineral wool M3 / M5	0.053 / 0.064 (Condition A)	ShNQ 2.01.04-2018 (2024 revision)
λ: Foam glass / EPS / XPS	0.048 / 0.036 / 0.032	Reference mean values
λ: PUR / PIR	0.025 / 0.022	Reference mean values
Gas tariff, UZS/m³	1,100 (residential ≤500 m³/mo); 2,000 (other)	Resolution No. 243 (effective June 2026)
Electric tariff, UZS/kWh	1,100 (501–1,000 kWh/mo)	Resolution No. 243 (effective June 2026)
Heat energy cost p, UZS/kWh	131 (gas 1,100); 239 (gas 2,000); 1,100 (electric)	Based on 9.3 kWh/m³ & 0.90 boiler efficiency
Discount rate r, period N	15%; 20 years (PVF = 6.26)	Conditional financial baseline

Note: Tariffs are subject to change; proposals to raise heating tariffs are under consideration, requiring sensitivity analysis.

Table 2. Conditional Material Unit Cost Scenario

Material	c_v, UZS/m³ (conditional)	50 mm layer cost, UZS/m²
Mineral wool M3	650,000	32,500
Mineral wool M5	900,000	45,000
Foam glass	2,800,000	140,000
EPS	400,000	20,000
XPS	800,000	40,000
PUR	1,500,000	75,000
PIR	1,700,000	85,000

Note: Material prices represent conditional scenario ratios rather than binding commercial quotes. Open listings show XPS 50 mm at ~30,600 UZS (unit unverified). Thus, price-independent criteria are evaluated separately in Section 3.4.

RESULTS

Uninsulated Floor Heat Loss and Effect of a 50 mm Insulation Layer

Annual heat loss of the baseline uninsulated floor was determined at 20.5 kWh/m² (totaling approximately 2,460 kWh/year for the 120 m² building) [4]. This specific heat loss is noticeably lower than that through external walls or roofs because the underlying soil mass provides substantial additional thermal resistance [5]. Applying a 50 mm insulation layer across the floor reduces annual heat loss to 14.8 kWh/m² for Mineral Wool M3, 12.5 kWh/m² for XPS, and 10.7 kWh/m² for PIR (Table 3). The performance ranking among materials follows PIR > PUR > XPS > EPS > Mineral Wool, although whole-floor average savings are lower than in Zone I due to higher baseline resistance in inner zones II and III [6].

Table 3. Energy and Monetary Savings of 50 mm Insulation Layer (Entire Floor, per 1 m²)

Material	E, kWh/m²	ΔE, kWh/m²	ΔE, %	Gas 1,100, UZS/yr	Gas 2,000, UZS/yr	Electric, UZS/yr
Mineral wool M3	14.8	5.7	27.8%	749	1,362	6,271
Mineral wool M5	15.5	5.0	24.3%	653	1,188	5,467
Foam glass	14.4	6.1	29.8%	803	1,460	6,721
EPS	13.1	7.4	36.1%	970	1,764	8,121
XPS	12.5	7.9	38.7%	1,043	1,896	8,728
PUR	11.3	9.1	44.6%	1,200	2,182	10,046
PIR	10.7	9.8	47.7%	1,284	2,334	10,743

Note: Uninsulated baseline loss E_0 = 20.5 kWh/m² per year. Source: Authors' calculations.

Payback Period Analysis

Under conditional prices, the simple payback period depends fundamentally on heating energy type (Table 4). With electric heating, EPS achieves simple payback in 2.5 years, XPS in 4.6 years, and Mineral Wool M3 in 5.2 years [7]. Under residential natural gas tariffs (1,100 UZS/m³), even the most economical option (EPS) requires more than 20.6 years, indicating that full floor insulation is not financially justified purely on energy savings under subsidized gas tariffs. If gas is priced at the commercial tariff (2,000 UZS/m³), payback for EPS drops to 11.3 years. Foam glass and high-cost PIR/PUR offer reasonable payback periods exclusively under electric heating [8].

Table 4. Simple Payback Period for Entire Floor vs. Perimeter (Zone I) Insulation, years (50 mm layer)

Material	Full: Gas 1,100	Full: Gas 2,000	Full: Electric	Zone I: Gas 1,100	Zone I: Gas 2,000	Zone I: Electric
Mineral wool M3	43.4	23.9	5.2	30.4	16.7	3.6
Foam glass	174.4	95.9	20.8	122.2	67.2	14.6
EPS	20.6	11.3	2.5	14.5	8.0	1.7
XPS	38.4	21.1	4.6	27.1	14.9	3.2
PUR	62.5	34.4	7.5	44.5	24.5	5.3
PIR	66.2	36.4	7.9	47.3	26.0	5.7

Note: For Mineral wool M5 across full floor: 68.9, 37.9, and 8.2 years respectively. Source: Authors' calculations.

Insulating perimeter Zone I exclusively yields 1.4 times higher energy savings per unit area (e.g., 11.2 kWh/m² vs 7.9 kWh/m² for XPS), thereby reducing simple payback periods by approximately 30%. This confirms the thermal and economic superiority of perimeter insulation [9].

Economically Optimal Insulation Thickness

Life-cycle costs (Equation 5) were evaluated for insulation thicknesses ranging from 20 mm to 200 mm in 10 mm increments (Table 5). Under electric heating, optimal thickness across the entire floor is approximately 90 mm for EPS, 40 mm for XPS and Mineral Wool M3, and ~20 mm for PUR and PIR [10]. Analytical optimal calculations (Equation 6) for perimeter Zone I yield 109 mm for EPS, 65 mm for M3, 56 mm for XPS, 27 mm for PUR, and 24 mm for PIR. Under gas heating (both 1,100 and 2,000 UZS/m³), insulation thicker than 20 mm is not economically justified (LCC reduction is negative or near zero) [11].

Table 5. Optimal Thickness and LCC Reduction Under Electric Heating (Entire Floor)

Material	δ_opt (grid search), mm	LCC Reduction, UZS/m²	Economic Conclusion
EPS	90	34,512	Optimal & Highly Cost-Effective
XPS	40	15,528	Optimal & Cost-Effective
Mineral wool M3	40	7,345	Optimal & Cost-Effective
PUR	20 or less	4,828	Limited Feasibility
PIR	20 or less	4,230	Limited Feasibility
Mineral wool M5	—	-1,834	Unjustified
Foam glass	—	-35,283	Unjustified

Note: Parameters r = 15%, N = 20 years, p = 1,100 UZS/kWh; minimum thickness constrained at 20 mm. Source: Authors' calculations.

Price-Independent Criterion: Maximum Allowable Cost

To provide a market-resilient decision tool independent of fluctuating material price quotes, the maximum allowable unit area cost for a 50 mm layer corresponding to a target 10-year simple payback period was calculated (Table 6). For instance, under residential gas tariffs, a 50 mm XPS layer must cost no more than 10,428 UZS/m² (~208,600 UZS/m³) to recover investment in 10 years. Under electric heating, this threshold increases significantly to 87,282 UZS/m² [12].

Table 6. Maximum Allowable Cost for 10-Year Simple Payback, UZS/m² (50 mm Layer, Entire Floor)

Material	Gas 1,100 UZS/m³	Gas 2,000 UZS/m³	Electric 1,100 UZS/kWh
Mineral wool M3	7,492	13,623	62,711
Mineral wool M5	6,532	11,876	54,670
Foam glass	8,030	14,600	67,209
EPS	9,702	17,641	81,209
XPS	10,428	18,960	87,282
PUR	12,002	21,822	100,458
PIR	12,835	23,336	107,429

Note: Maximum allowable cost = annual monetary savings × 10 years. Source: Authors' calculations.

DISCUSSION

The findings demonstrate two key energy-economic insights. First, because heat loss through ground-connected slabs is moderate, full-floor insulation in natural gas-heated residential buildings yields low financial returns under current gas tariffs; in such cases, insulation thickness is dictated primarily by normative thermal resistance standards (ShNQ 2.01.04-2018) rather than economic optimization, with purely economic optimums staying below 20 mm. Second, in buildings utilizing electric heating, off-grid gas regions, or commercial gas tariffs (2,000 UZS/m³), insulation is highly cost-effective, with optimal thicknesses reaching 40–90 mm. Anticipated energy tariff increases will further enhance the economic viability of floor insulation [13].

Material selection must balance financial metrics with structural and environmental performance:

a. EPS offers the highest financial return due to low cost, but compressive strength and moisture vulnerability must be verified;
b. XPS provides superior moisture resistance and compressive strength under direct contact with damp soil;
c. PIR and PUR excel where strict space/thickness limits exist;
d. Foam glass is justified under extreme load-bearing or high-moisture conditions;
e. Mineral wool design values account for operating moisture corrections (λA, λB), whereas cellular polymer values are nominal (dry), giving polymers a slight analytical advantage [14].

Study Limitations:

a. Material prices are conditional baseline assumptions requiring local market quote verification;
b. Heating degree-days (Dd = 2,300 °C·days) is an estimated figure requiring exact regional standardization from ShNQ 2.01.01-22;
c. Zonal calculation method assumes steady-state heat transfer without dynamic ground thermal inertia;
d. Costs associated with installation labor, waterproofing membranes, maintenance, and energy price escalation were omitted;
e. Reference mean thermal conductivity values were used for synthetic polymers;
f. Actual boiler efficiency varies based on equipment type and operating regime [15].

CONCLUSION

For Samarkand's climate (Dd ≈ 2,300 °C·days) in a 120 m² reference building, uninsulated ground floor heat loss is 20.5 kWh/m² per year. A 50 mm insulation layer reduces heat loss by 24.3% (Mineral Wool M5) to 47.7% (PIR). Energy carrier type governs economic feasibility: simple payback under electric heating is 2.5 years (EPS), 4.6 years (XPS), and 5.2 years (Mineral Wool M3), whereas under residential natural gas tariffs (1,100 UZS/m³) payback exceeds 20.6 years. Economically optimal insulation thickness under electric heating is ~90 mm for EPS and 40 mm for XPS and dense mineral wool. Under natural gas tariffs, insulation >20 mm is economically unjustified, and thickness should be determined by normative standards. Perimeter-only (Zone I) insulation generates 1.4 times higher energy savings per m² and reduces simple payback periods by ~30%, making it the most cost-effective partial strategy. Price-independent allowable cost thresholds for a 10-year payback (50 mm layer: 6,532–12,835 UZS/m² for gas; 54,670–107,429 UZS/m² for electric heating) serve as objective guidelines for commercial procurement.

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