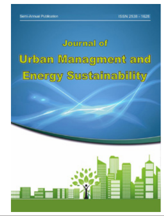
Int. J. Urban Manage. Energy Sustainability, 6(2):327-339, 2025

International Journal of Urban Management and Energy Sustainability (IJUMES)

Homepage: http://www.ijumes.com



CASE STUDY RESEARCH PAPER

Energy Consumption of Contemporary Office Buildings Based on Envelope Materials and Building Dimensions: A Simulation-Based Study in a Semi-Arid Climate (Case Study: Tehran City, Iran)

Seyedmahmood Moeini[1*], Mahdi Shaabanian[2], Saeid Saeidipour[3], Zahra Moradi[2]

*1*Department of Architecture, Mal.C., Islamic Azad University, Malayer, Iran*

2 Department of Architecture, Ha.C., Islamic Azad University, Hamedan, Iran

3 Department of Architecture, Karazin Kharkiv National University, Kharkiv, Ukraine

ARTICLE INFO

Article History:
Received 2025-01-05
Revised 2025-03-06
Accepted 2025-06-08

Keywords:
Building envelope, energy simulation, contemporary office buildings, semi-arid climate, window-to-wall ratio

DOI: 10.22034/ijumes.2025.735602

ABSTRACT

Buildings are responsible for roughly one-third of global final energy use, and contemporary office buildings rank among the most energy-intensive segments of the non-residential stock. In hot, semi-arid climates the combined influence of envelope material selection and overall building dimensions on office energy demand remains insufficiently quantified, because designers commonly treat thermal and geometric decisions in isolation. This study evaluates how envelope materials (wall insulation, glazing, and roof finish) and building dimensions (window-to-wall ratio, plan aspect ratio, and number of floors) jointly govern the annual energy consumption of a representative contemporary mid-rise office building in Tehran. A validated Design Builder/Energy Plus parametric model was employed, varying one factor at a time across realistic ranges and benchmarking outcomes against Iran's National Building Code (Topic 19). Model reliability was confirmed against measured indoor temperatures (R^2 = 0.89; RMSE = 1.1 °C). Results show the demand is strongly cooling-dominated and that glazing type and window-to-wall ratio are the most influential parameters: replacing single glazing with double low-emissivity units lowered energy use intensity (EUI) by about 22%, while an optimal window-to-wall ratio near 30% minimized the total load. Wall insulation captured most of its benefit within the first 5–7 cm, and compact forms (lower aspect ratio, greater height) reduced EUI by roughly 10%. A combined material–dimensional optimization reduced EUI by about 19% (from 150 to 121 kWh/m²·yr). It is concluded that material and dimensional decisions must be co-optimized rather than addressed separately for cost-effective, low-energy contemporary office design in semi-arid regions.

Running Title: Energy Consumption of Office Buildings by Materials and Dimensions

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
35	08	06

*Corresponding Author:
Email: *mmoeini.arch@iau.ac.ir*
Phone: + 988132228093
ORCID: https://orcid.org/0009-0007-8957-9918

INTRODUCTION

The building sector consumes close to one-third of global final energy and is a major contributor to anthropogenic greenhouse-gas emissions, a share that continues to grow with urbanization and rising service demand (Berardi, 2015; Santamouris & Vasilakopoulou, 2021). Within this sector, office buildings are disproportionately energy-intensive: dense internal gains from occupants, lighting and equipment interact with large glazed envelopes to produce cooling-dominated load profiles that are highly sensitive to design decisions (Pino, Bustamante, Escobar, & Pino, 2012; Luo, Liu, & Liu, 2016). Because the envelope mediates virtually all heat exchange between the conditioned interior and the outdoor environment, both the materials that compose it and the dimensions that define its exposed area are decisive for a building's energy performance. The problem is particularly acute in hot, semi-arid regions such as the Iranian plateau, where intense solar radiation and wide diurnal temperature swings amplify cooling loads while heating remains non-trivial in winter (Ghiai, Arjmand, & Mohammadi, 2021; Reyes-Barajas, Romero-Moreno, Sotelo-Salas, Luna-León, & Bojórquez-Morales, 2020). Iran's National Building Code (Topic 19) prescribes envelope thermal requirements, yet design practice frequently optimizes individual measures, such as adding insulation or changing glass, without accounting for how building geometry re-weights their effectiveness. As a result, the joint influence of envelope materials and building dimensions on office energy use is not well quantified for this climate. A key reason the two families of decisions cannot be separated is that they act on the same heat-transfer pathways. The energy penalty of a large window depends on the glass specified; the value of wall insulation depends on how much opaque wall the building's proportions actually expose; and the benefit of a compact form depends on the reflectivity and insulation of the roof that compactness makes proportionally larger or smaller. Treating any one factor as fixed while optimizing another therefore risks recommending a locally optimal but globally sub-optimal envelope. This motivates an evaluation that varies material and dimensional factors within one consistent model. Accordingly, the objective of this study is to evaluate, through validated building-energy simulation, how a coherent set of material variables (wall-insulation thickness, glazing system, and roof finish) and dimensional variables (window-to-wall ratio, plan aspect ratio, and number of floors) shape the annual energy consumption of a representative mid-rise office building in Tehran, and to identify a cost-effective, code-compliant design package. The contribution is threefold: (i) a single, internally consistent parametric framework that places material and dimensional factors on a common energy-intensity scale; (ii) a sensitivity ranking that clarifies which decisions dominate in a BSk climate; and (iii) an optimized envelope–form combination benchmarked against Topic 19.

Envelope thermal behavior and the role of materials

The envelope governs 40–60% of a building's thermal load, so material properties, chiefly thermal conductivity, density, specific heat and solar absorptance, largely determine heating and cooling demand (Charles, Maref, & Ouellet-Plamondon, 2019). Adding thermal insulation is the most direct lever: comprehensive reviews confirm that insulation reduces conductive losses and that an economically optimal thickness exists beyond which returns diminish (Dickson & Pavía, 2021; Ozbek, Gelis, & Ozyurt, 2022). Response-surface analyses across climatic zones show optimal thicknesses scaling with heating degree-days, with cost-optimal values typically in the 5–10 cm range for temperate and semi-arid contexts (Ozbek et al., 2022). Material choice also carries an embodied-energy dimension, so envelope decisions increasingly weigh operational against life-cycle burdens (Shadram & Mukkavaara, 2019; Luo et al., 2016).

Beyond opaque walls, surface radiative properties matter. Reflective (“cool”) roof and wall finishes lower surface temperatures and cooling loads in warm climates, a mechanism extensively reviewed by Santamouris (2014) and quantified for schools and offices by Synnefa, Saliari, and Santamouris (2012). Retro-reflective materials extend this idea to dense urban settings by redirecting inter-building radiation (Wang, Liu, Meng, Gao, & Yuan, 2021). Because higher solar absorptance reduces winter heating but raises summer cooling, the net benefit is climate-specific and must be evaluated on an annual basis (Liu et al., 2025).

Glazing and fenestration

Glazing is typically the weakest thermal link and the strongest solar-gain pathway of an office envelope. Advances in double- and triple-glazed, low-emissivity and gas-filled units substantially cut both U-value and solar heat-gain coefficient (SHGC), improving performance across heating- and cooling-dominated climates (Li & Wu, 2025; Xamán, Pérez-Nucamendi, Arce, Hinojosa, & Álvarez, 2014). Dynamic and double-skin façade systems provide a further layer of control, reducing cooling demand through ventilation and adjustable shading (Lin, Song, & Chu, 2022; Vakilinezhad, 2023). Because fenestration simultaneously drives cooling, heating and lighting energy, glass selection is best treated as a multi-objective problem rather than a single U-value target (Pellegrino, Cammarano, Lo Verso, & Corrado, 2017; Dubois & Blomsterberg, 2011).

Building dimensions, geometry and window-to-wall ratio

Building dimensions influence energy use through two coupled mechanisms: the ratio of exposed envelope area to conditioned volume (compactness) and the proportion of that envelope that is transparent. Compact forms with a low surface-to-volume ratio lose and gain less heat per unit floor area, so elongated plans generally raise demand while taller, squarer massings improve it, an effect confirmed across climates and building types (Kistelegdi, 2022; Loonen, Trčka, Cóstola, & Hensen, 2013). The window-to-wall ratio (WWR) is the single most studied dimensional parameter for offices. Goia (2016) established that an optimal WWR minimizing combined heating, cooling and lighting energy exists for each climate and orientation, typically between 30% and 45% in temperate Europe. Similar optima, shifted by climate, have been reported for offices in China (Xue, Li, Xie, Zhao, & Liu, 2019), Bangladesh (Rana, Hasan, Sobuz, & Tam, 2022; Hossain, 2019), and Iran (Ghiai et al., 2021). Window size, however, is not purely an energy variable: it shapes daylight, view and occupant satisfaction, so optima derived from energy alone may conflict with those from comfort and productivity (Yeom, Kim, Hong, & Lee, 2020; Hong, Lee, Yeom, & Jeong, 2019; Pastore & Andersen, 2022). This tension motivates treating WWR jointly with glazing type and orientation, and, where possible, with passive façade logic and adaptive shading (Fabbri & Gaspari, 2021). Courtyard and self-shading geometries offer a further dimensional strategy well suited to hot-arid contexts (Haseh, Khakzand, & Ojaghlou, 2018).

Simulation, optimization and the research gap

Whole-building simulation tools such as EnergyPlus and DesignBuilder have become the standard means of quantifying these interactions, with results validated repeatedly against measurements (Liu et al., 2025; Ghiai et al., 2021). On this foundation, multi-objective and machine-learning approaches now search envelope–system design spaces for energy-, comfort- and cost-optimal solutions (Wang, Lu, & Feng, 2020; Zhou & Zheng, 2020; Peng, Rysanek, Nagy, & Schlüter, 2018). Nevertheless, most studies isolate a single family of variables, either materials (insulation, glazing, cool surfaces) or dimensions (WWR, form), so their conclusions cannot indicate which lever dominates once the two are considered together. Retrofit-oriented work on offices in hot climates further shows that material upgrades and geometric constraints interact strongly (Vakilinezhad, 2023; Charles et al., 2019). The present study addresses this gap by evaluating material and dimensional variables within one validated parametric model for a semi-arid office building, enabling a direct, common-scale comparison and a code-referenced optimal package.

Energy codes and the semi-arid Iranian context

Regulatory frameworks translate the physics above into enforceable limits. Most codes set maximum U-values for opaque and transparent elements and, in some cases, prescriptive shape or glazing-ratio provisions; several European codes even relax insulation requirements for more compact forms, implicitly rewarding a favorable surface-to-volume ratio (Loonen et al., 2013). Iran's National Building Code (Topic 19, Energy Conservation) follows a comparable logic, defining envelope thermal transmittance ceilings differentiated by climatic zone and building importance. However, enforcement gaps and a design culture that upgrades single measures in isolation mean that the code's savings potential is often only partially realized in the office stock (Ghiai et al., 2021). Tehran's cold semi-arid (BSk) climate makes this a demanding test case. Summers are hot and largely clear, producing strong solar loads on glazing and on horizontal roof surfaces, while winters are cold enough to impose a real, if smaller, heating penalty. Passive responses well documented for such climates, self-shading courtyard geometries (Haseh et al., 2018), high-albedo roofs and walls (Santamouris, 2014; Synnefa et al., 2012), and carefully sized, low-SHGC fenestration (Xamán et al., 2014), form the practical vocabulary from which an optimal office envelope can be assembled. The remainder of this paper quantifies how far these material and dimensional strategies can carry an office building within the Topic 19 envelope.

MATERIALS AND METHODS

This applied, quantitative study uses a simulation-based, single-case parametric strategy. A representative mid-rise office building typical of central Tehran was defined as a baseline, modelled in DesignBuilder (EnergyPlus engine), and validated against field temperature measurements. Six design parameters, three material and three dimensional, were then varied one at a time across realistic ranges (a one-factor-at-a-time design), and the resulting annual energy use intensity (EUI, kWh/m²·yr) was recorded and compared with the Topic 19 baseline. Finally, the individually best-performing levels were combined into an optimised scenario. Figure 1 summarises the workflow. (Fig. 1)

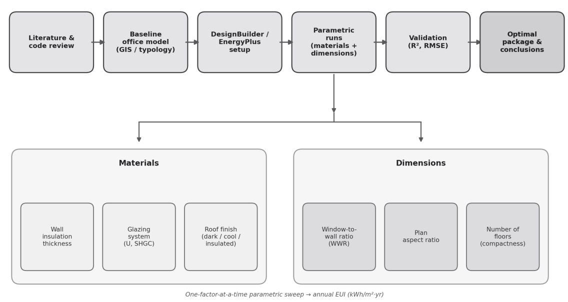


Figure 1: Research process and analytical workflow of the study.

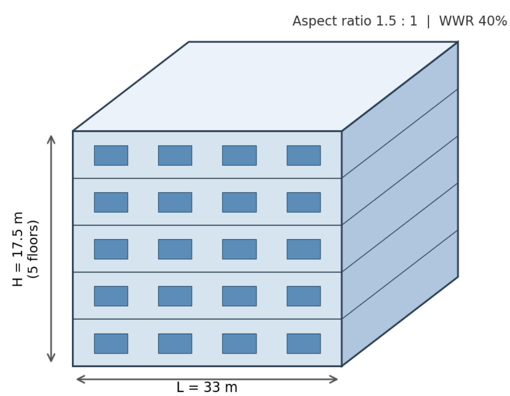


Figure 2: Baseline mid-rise office model (five floors, aspect ratio 1.5:1, WWR 40%) used as the reference case.

Baseline building and climate

The baseline is a five-story rectangular office block with a gross floor area of 3,000 m², a plan aspect ratio of 1.5:1, and a window-to-wall ratio of 40% distributed on the principal north–south façades (Fig. 2). Occupancy, lighting and equipment schedules follow a standard 08:00–18:00 office profile. Heating and cooling set-points were fixed at 21 °C and 25 °C respectively, with an ideal-loads HVAC system so that the analysis isolates envelope and form effects. Tehran lies in a cold semi-arid (BSk) climate; the weather file and degree-day data used are summarized in Table 2. Table 1 lists the fixed baseline parameters, and Table 3 the thermophysical properties of the materials examined. (Fig. 2, Tab. 1 to 3)

Table 1: Fixed geometric and operational parameters of the baseline office model.

Parameter	Value
Land use / occupancy	Office (08:00–18:00 weekday schedule)
Gross floor area	3,000 m² (600 m² × 5 floors)
Number of floors / heights	5 floors / 17.5 m
Plan aspect ratio (L:W)	1.5 : 1 (33 m × 22 m)
Window-to-wall ratio (baseline)	40% (N–S oriented)
Heating / cooling set-point	21 °C / 25 °C
Occupant / equipment density	0.11 person/m² / 12 W/m²
Lighting power density	9 W/m² (daylight-linked)
Infiltration	0.5 ach

Table 2: Geographic and climatic data for Tehran (Köppen BSk).

Latitude	Longitude	Elevation (m)	Heating degree-days	Cooling degree-days
35.69° N	51.39° E	1,191	1,495	1,378

Table 3: Thermophysical properties of the envelope materials evaluated.

Material	Conductivity λ (W/m·K)	Density ρ (kg/m³)	Specific heat c (J/kg·K)
Fired-clay brick	0.72	1,920	840
Cement–sand mortar	0.93	1,860	840
Rock-wool insulation	0.040	100	840
Expanded polystyrene (EPS)	0.038	35	1,400
Reinforced concrete (roof)	2.00	2,400	880
Gypsum plaster (internal)	0.40	1,000	1,000

Parametric variables

Three material and three-dimensional variables were investigated. Materials: (i) rock-wool wall-insulation thickness (0, 3, 5, 7, 10 cm); (ii) glazing system (single clear, double clear, double low-E with argon, triple low-E with argon), whose optical/thermal data appear in Table 5; and (iii) roof finish (uninsulated dark, insulated dark, insulated with a high-albedo cool coating). Dimensions: (iv) window-to-wall ratio (20–70% in 10-point steps); (v) plan aspect ratio (1.0–3.0 at constant floor area); and (vi) number of floors (3, 5, 7, 10 at constant total floor area, i.e. varying compactness). The wall assemblies and their resulting U-values are given in Table 4. (Tab. 4 and 5)

Table 4: Wall assemblies and overall U-values for the insulation-thickness scenarios.

Scenario	Insulation (rock wool)	Wall thickness (cm)	U-value (W/m²·K)
W0	None	23	1.28
W1	3 cm	26	0.71
W2 (baseline)	5 cm	28	0.52
W3	7 cm	30	0.41
W4	10 cm	33	0.31

Table 5: Optical and thermal properties of the glazing systems evaluated.

Glazing system	U-value (W/m²·K)	SHGC	Visible transmittance
Single clear (6 mm)	5.78	0.82	0.88
Double clear (6-13-6, air)	2.70	0.70	0.78
Double low-E (6-13-6, argon)	1.60	0.42	0.71
Triple low-E (argon)	0.90	0.36	0.66

Governing relationships

Three quantities anchor the analysis. Energy use intensity, the common metric on which all scenarios are compared, is the total annual delivered energy normalised by conditioned floor area:

$$EUI = (Qheat + Qcool + Qlight) / Afloor \quad (1)$$

Compactness is expressed through the surface-to-volume ratio, which links the dimensional variables to envelope heat exchange:

$$S/V = Aenvelope / Vconditioned \quad (2)$$

Finally, the cost-optimal insulation thickness that balances material cost against the present value of energy savings, used to interpret the diminishing-return behaviour in Section 4.1, follows the classical degree-day form (Ozbek et al., 2022):

$$\delta opt = \sqrt{(0.0052 \cdot PWF \cdot (HDD/EER + CDD/COP) \cdot \lambda ins / Ci)} - Rwt \cdot \lambda ins \quad (3)$$

where PWF is the present-worth factor, HDD and CDD the heating and cooling degree-days, EER and COP the seasonal system efficiencies, λ the insulation conductivity, C the unit insulation cost and R the base-wall resistance. Model reliability was quantified with the coefficient of determination (R^2) and the root-mean-square error (RMSE) between simulated and measured indoor temperatures.

Software configuration and validation

Design Builder was chosen because its Energy Plus core resolves transient, multi-zone heat balances and has been validated in numerous analytical, comparative and empirical studies (Liu et al., 2025). Internal gains, natural ventilation and mechanical-system dynamics were held constant so that only the envelope and form of the building affect the reported loads. To confirm reliability, simulated mid-floor indoor temperatures were compared with hourly measurements collected over representative summer and winter periods with all mechanical systems off. The comparison (Section 4.5) yielded a coefficient of determination of R^2 = 0.89 and a root-mean-square error of 1.1 °C, well within accepted tolerances and consistent with validation levels reported for comparable office models (Ghiai et al., 2021).

FINDINGS AND DISCUSSION

Effect of wall-insulation thickness

Increasing rock-wool thickness reduced heating demand steadily but had only a marginal effect on the cooling-dominated total load (Fig. 3). Relative to an uninsulated wall (168 kWh/m²), the 5 cm and 7 cm cases reached 150 and 147 kWh/m², a 10.7% and 12.5% reduction, while extending to 10 cm produced only a further 1.1% saving. The curve exhibits the classic diminishing-return behavior: most of the achievable benefit is captured within the first 5–7 cm, beyond which added material yields little annual energy improvement in this climate, consistent with the cost-optimal ranges reported by Ozbek et al. (2022) and Dickson and Pavía (2021). (Fig. 3)

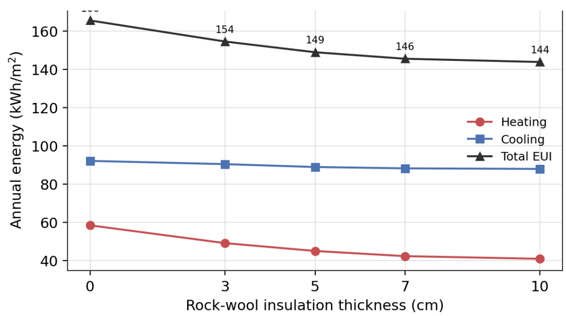


Figure 3: Annual heating, cooling and total energy use intensity as a function of rock-wool wall-insulation thickness.

The asymmetry between heating and cooling responses is instructive. Insulation strongly suppresses winter conductive losses, so heating energy falls by nearly 30% from the uninsulated to the 10 cm case; cooling, however, barely changes, because in a cooling-dominated office the dominant summer load enters through glazing and internal gains rather than through the opaque wall, and thick insulation can even trap internal heat, marginally raising cooling. This confirms that opaque-wall insulation is necessary but not sufficient in semi-arid offices, and that its economic optimum, obtained from Equation (3), sits well below the maximum feasible thickness (Dickson & Pavía, 2021; Ozbek et al., 2022).

Effect of glazing system

Glazing exerted the largest single influence on total energy use (Figure 4). Replacing single clear glass (172 kWh/m²) with double clear cut EUI to 150 kWh/m², and with double low-E (argon) to 139 kWh/m², a 22% reduction driven almost entirely by lower cooling demand as the solar heat-gain coefficient fell from 0.82 to 0.42. Triple low-E gave a further, smaller gain (135 kWh/m²). Because the office is cooling-dominated, controlling solar transmission is more valuable than reducing conductive U-value alone, in agreement with the multi-objective findings of Pellegrino et al. (2017) and Xamán et al. (2014). (Fig. 4)

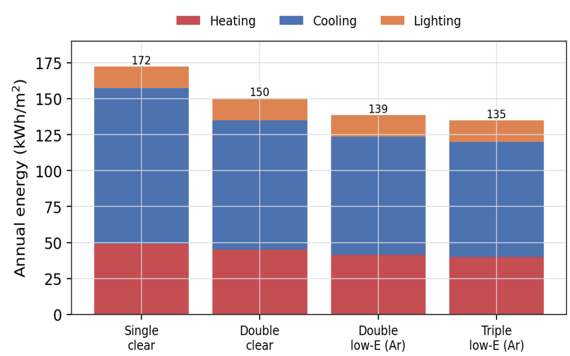


Figure 4: Disaggregated annual energy use intensity (heating, cooling, lighting) for the four glazing systems.

Effect of window-to-wall ratio

Total EUI followed a shallow U-shape against WWR, with a minimum near 30% (Figure 5). Below the optimum, lighting energy rose sharply as daylight availability fell; above it, cooling energy climbed steeply with additional solar and conductive gains. Moving from 30% to 70% increased EUI by roughly 16%. The existence and location of this optimum agree closely with Goia (2016) for temperate offices and with the climate-shifted optima reported by Xue et al. (2019) and Rana et al. (2022). As window size also affects daylight and view quality, the energy optimum should be read alongside comfort considerations (Yeom et al., 2020; Hong et al., 2019). (Fig. 5)

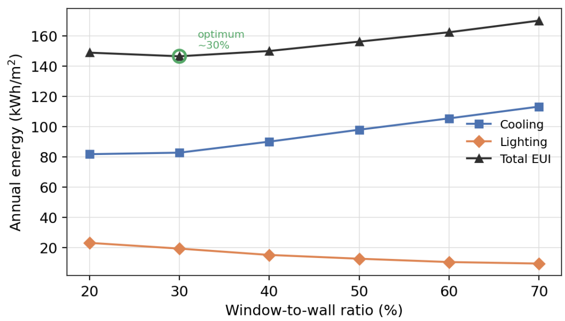


Figure 5: Cooling, lighting and total energy use intensity as a function of window-to-wall ratio; the optimum lies near 30%.

Two interactions deserve emphasis. First, the WWR optimum is contingent on glazing: with double low-E glass the cooling penalty of a larger window is muted, flattening the curve and shifting the optimum slightly upward, whereas with single glazing the penalty is severe and the optimum drops below 30%. This coupling explains why fenestration proportion and glass type must be chosen together rather than sequentially (Goia, 2016; Xamán et al., 2014). Second, orientation matters: concentrating glazing on the north–south axis, as in the baseline, exploits controllable low-altitude winter sun while limiting harsh east–west summer gains, a strategy repeatedly validated for hot climates (Hossain, 2019; Reyes-Barajas et al., 2020).

Effect of building dimensions: aspect ratio and height

Dimensional variables shifted EUI through compactness (Figure 6). Elongating the plan from a 1.0:1 square to 3.0:1 raised the surface-to-volume ratio from 0.29 to 0.45 m$^{□1}$ and increased EUI from 147 to 163 kWh/m^2 (+10.4%), because a larger exposed envelope admits more heat per unit floor area. Conversely, increasing the number of floors at constant total area, i.e. a more compact, taller massing, lowered EUI from 155 kWh/m^2 (3 floors) to 146 kWh/m^2 (10 floors), as the roof and ground-contact fractions shrank. These trends corroborate the compactness principles reviewed by Loonen et al. (2013) and Kistelegdi (2022) and confirm that form is a genuine, if secondary, energy lever. (Fig. 6)

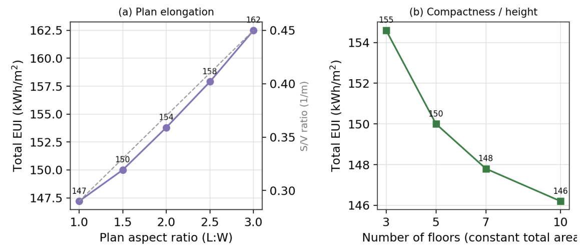


Figure 6: Influence of (a) plan aspect ratio and (b) number of floors (constant total floor area) on total energy use intensity.

The magnitude of the dimensional effect is climate-dependent and interacts with the material layer. In a cooling-dominated context, a larger exposed envelope is a mixed blessing: it increases conductive gains but also enlarges the north-facing area available for controlled daylighting, partially offsetting lighting energy. The net penalty of elongation observed here (+10%) is therefore smaller than would be expected in a purely heating-driven climate, where envelope losses dominate unambiguously. Likewise, the benefit of added height plateaus once the roof fraction, the surface most exposed to solar and long-wave radiation, becomes small relative to the walls, at which point roof reflectivity and insulation (Section 4.5) become the more effective roof-related lever than further compactness (Santamouris, 2014; Wang et al., 2021).

Relative sensitivity and validation

Ranking the parameters by the EUI swing they produce across their tested ranges (Figure 7) places glazing type first (37.4 kWh/m^2), followed closely by window-to-wall ratio and wall-insulation thickness, then plan aspect ratio, roof treatment and number of floors. The ordering confirms that, for a semi-arid office, the transparent envelope and its extent dominate, material and dimensional decisions about the opaque envelope and massing are meaningful but secondary. The validation regression (Figure 8b) supports these findings, with simulated and measured indoor temperatures clustering tightly around the identity line (R^2 = 0.89, RMSE = 1.1 °C). (Fig. 7)

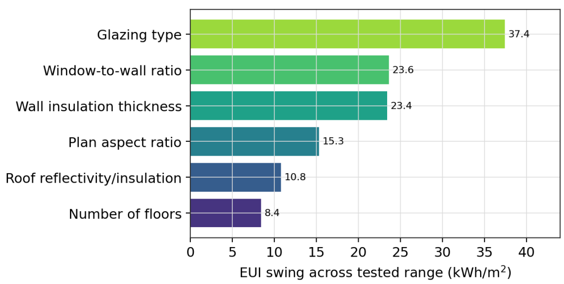


Figure 7: Sensitivity ranking of the six design parameters by the energy-use-intensity swing across their tested ranges.

Comparison with prior studies and practical implications

The results align with, and extend, the fragmented findings of earlier single-variable work. The 30% window-to-wall optimum sits at the lower edge of Goia's (2016) 30–45% European band, as expected for a more strongly cooling-driven climate, and matches the climate-shifted optima reported for low-latitude Chinese and South-Asian offices (Xue et al., 2019; Rana et al., 2022; Hossain, 2019). The 22% saving from low-emissivity glazing is consistent with the solar-control benefits documented by Xamán et al. (2014) and the double-skin retrofit gains of Vakilinezhad (2023) and Lin et al. (2022). The compactness effect, an approximately 10% EUI change across the aspect-ratio range, reproduces the shape-factor sensitivities synthesized by Loonen et al. (2013) and Kistelegdi (2022). The novel contribution is placing all six levers on one energy-intensity scale, which exposes their hierarchy: transparent-envelope decisions (glazing and WWR) outweigh opaque-envelope and massing decisions in a semi-arid office. For practice, this suggests a clear design sequence, first fix glazing type and fenestration proportion, then compactness and roof treatment, and finally tune wall insulation to its economic threshold. Because every optimized level remains within Topic 19 limits, the 19% saving is achievable through better selection and proportioning of conventional, locally available components rather than through exotic technologies, a conclusion with direct relevance to the large, code-governed office stock of Tehran and comparable cities.

RESULTS AND CONCLUSION

Combined optimization and code benchmarking

Combining the individually best levels, a compact plan (aspect ratio 1.2:1), a 30% north–south WWR, double low-E argon glazing, 7 cm rockwool walls, and an insulated cool roof, produced an optimized office with an EUI of 121 kWh/m²·yr, a 19.1% reduction from the 150 kWh/m² baseline (Figure 8a and Table 6). Cooling, the dominant end use, fell by 21.8% and lighting by 17.3%, while heating declined more modestly. All optimised assemblies satisfy the U-value ceilings of Iran's National Building Code (Topic 19), confirming that substantial savings are attainable within, rather than beyond, existing regulatory limits, echoing the retrofit gains reported for hot-climate offices by Vakilinezhad (2023) and Charles et al. (2019). (Fig. 8 and Tab. 6)

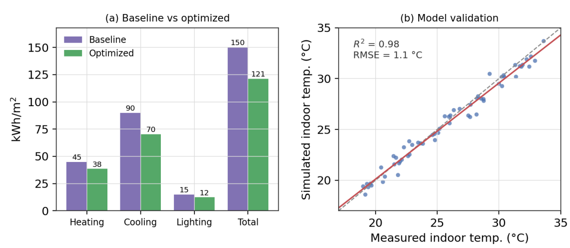


Figure 8: (a) Baseline versus optimised annual energy use intensity by end use; (b) validation of simulated against measured indoor temperatures.

This study evaluated, within a single validated simulation framework, how envelope materials and building dimensions jointly determine the energy consumption of an office building in a semi-arid climate. Three conclusions stand out.

First, the demand is strongly cooling-dominated, so measures that control solar gain, chiefly low-emissivity glazing and a moderate window-to-wall ratio near 30%, deliver the greatest savings, outranking opaque-wall insulation once the first 5–7 cm is in place. Second, dimensional decisions are real but secondary: compact, taller massings reduce EUI by roughly 10% through a lower surface-to-volume ratio. Third, material and dimensional levers interact, so co-optimising them yielded a 19% reduction in energy use intensity while remaining fully compliant with Topic 19. For designers in hot, semi-arid regions, the practical implication is to prioritise glazing and fenestration proportion, then form compactness, and to treat wall insulation as a threshold rather than a maximise-at-all-costs measure.

Table 6: Summary of parametric scenarios and resulting annual energy use intensity (EUI).

Design variable	Range tested	Best level	EUI at best (kWh/m²)
Wall insulation thickness	0–10 cm	7 cm	147
Glazing system	Single – triple low-E	Double low-E (argon)	139
Roof finish	Dark – cool + insulated	Cool + insulated	148
Window-to-wall ratio	20–70%	30%	146
Plan aspect ratio	1.0–3.0	1.0–1.2	147
Number of floors	3–10	10	146
Combined optimum	–	All above	121

Limitations and Future Work

The one-factor-at-a-time design isolates individual effects but does not capture the full interaction surface; future work should employ multi-objective optimisation and machine-learning surrogates to explore the coupled design space efficiently (Wang et al., 2020; Zhou & Zheng, 2020; Peng et al., 2018). Extending the analysis to embodied energy and life-cycle cost (Shadram & Mukkavaara, 2019), to adaptive and double-skin façades (Lin et al., 2022; Fabbri & Gaspari, 2021), and to occupant comfort and daylight metrics (Pastore & Andersen, 2022) would broaden the evaluation beyond operational energy alone.

NOMENCLATURE

Symbol / abbreviation	Definition	Symbol / abbreviation	Definition
EUI	Energy use intensity (kWh/m²·yr)	SHGC	Solar heat-gain coefficient (–)
WWR	Window-to-wall ratio (%)	U	Thermal transmittance (W/m²·K)
S/V	Surface-to-volume ratio (1/m)	λ	Thermal conductivity (W/m·K)
HDD / CDD	Heating / cooling degree-days	ρ	Density (kg/m³)
BSk	Cold semi-arid climate (Köppen)	low-E	Low-emissivity glazing
R^2 / RMSE	Coefficient of determination / root-mean-square error	Topic 19	Iran National Building Code, energy part

REFERENCES

Berardi, U. (2015). Building energy consumption in the US, EU, and BRIC countries. Procedia Engineering, 118, 128–136. https://doi.org/10.1016/j.proeng.2015.08.411

Charles, A., Maref, W., & Ouellet-Plamondon, C. M. (2019). Case study of the upgrade of an existing office building for low energy consumption and low carbon emissions. Energy and Buildings, 183, 151–160. https://doi.org/10.1016/j.enbuild.2018.10.008

Dickson, T., & Pavía, S. (2021). Energy performance, environmental impact and cost of a range of insulation materials. Renewable and Sustainable Energy Reviews, 140, 110752. https://doi.org/10.1016/j.rser.2021.110752

Dubois, M.-C., & Blomsterberg, Å. (2011). Energy saving potential and strategies for electric lighting in future North European, low energy office buildings. Energy and Buildings, 43(10), 2572–2582. https://doi.org/10.1016/j.enbuild.2011.07.001

Fabbri, K., & Gaspari, J. (2021). A replicable methodology to evaluate passive façade performance with SMA during the architectural design process. Energies, 14(19), 6231. https://doi.org/10.3390/en14196231

Ghiai, M. M., Arjmand, J. T., & Mohammadi, O. (2021). Investigation and modeling of energy consumption of a tall office building in Iran's hot-arid and cold climate conditions. International Journal of Low-Carbon Technologies, 16(1), 21–34. https://doi.org/10.1093/ijlct/ctaa030

Goia, F. (2016). Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential. Solar Energy, 132, 467–492. https://doi.org/10.1016/j.solener.2016.03.031

Haseh, R. H., Khakzand, M., & Ojaghlou, M. (2018). Optimal thermal characteristics of the courtyard in the hot and arid climate of Isfahan. Buildings, 8(12), 166. https://doi.org/10.3390/buildings8120166

Hong, T., Lee, M., Yeom, S., & Jeong, K. (2019). Occupant responses on satisfaction with window size in physical and virtual built environments. Building and Environment, 166, 106409. https://doi.org/10.1016/j.buildenv.2019.106409

Hossain, M. S. (2019). A parametric study of window, orientation and shading to minimize energy consumption in mechanically ventilated high-rise office buildings in Dhaka, Bangladesh. Asia Pacific Journal of Energy and Environment, 6(2), 103–114. https://doi.org/10.18034/apjee.v6i2.271

Kistelegdi, I. (2022). Simulation-supported design of a high-rise office building envelope. Pollack Periodica, 17(1), 139–144. https://doi.org/10.1556/606.2021.00253

Li, X., & Wu, Y. (2025). A review of complex window-glazing systems for building energy saving and daylight comfort. Energy & Environment. Advance online publication. https://doi.org/10.1177/17442591241269182

Lin, Z., Song, Y., & Chu, Y. (2022). Summer performance of a naturally ventilated double-skin façade with adjustable glazed louvers for building energy retrofitting. Energy and Buildings, 267, 112163. https://doi.org/10.1016/j.enbuild.2022.112163

Liu, Z.-A., Li, Y., Hou, J., Tian, L., Wang, S., Hu, W., & Zhang, L. (2025). Impact of exterior envelope thermal performance on energy demand and optimization strategies for university teaching-office buildings. Scientific Reports, 15, 15171. https://doi.org/10.1038/s41598-025-00045-y

Loonen, R. C. G. M., Trčka, M., Cóstola, D., & Hensen, J. L. M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. Renewable and Sustainable Energy Reviews, 25, 483–493. https://doi.org/10.1016/j.rser.2013.04.016

Luo, Z., Liu, Y., & Liu, J. (2016). Embodied carbon emissions of office building: A case study of China's 78 office buildings. Building and Environment, 95, 365–371. https://doi.org/10.1016/j.buildenv.2015.09.018

Ozbek, K., Gelis, K., & Ozyurt, O. (2022). Optimization of external wall insulation thickness in buildings using response surface methodology. International Journal of Energy and Environmental Engineering, 13(4), 1367–1381. https://doi.org/10.1007/s40095-022-00490-9

Pastore, L., & Andersen, M. (2022). The influence of façade and space design on building occupants' indoor experience. Journal of Building Engi-

neering, 46, 103663. https://doi.org/10.1016/j.jobe.2021.103663

Pellegrino, A., Cammarano, S., Lo Verso, V. R. M., & Corrado, V. (2017). Impact of daylighting on total energy use in offices of varying architectural features in Italy: Results from a parametric study. Building and Environment, 113, 151–162. https://doi.org/10.1016/j.buildenv.2016.09.012

Peng, Y., Rysanek, A., Nagy, Z., & Schlüter, A. (2018). Using machine learning techniques for occupancy-prediction-based cooling control in office buildings. Applied Energy, 211, 1343–1358. https://doi.org/10.1016/j.apenergy.2017.12.002

Phillips, R., Troup, L., Fannon, D., & Eckelman, M. J. (2020). Triple bottom line sustainability assessment of window-to-wall ratio in US office buildings. Building and Environment, 182, 107057. https://doi.org/10.1016/j.buildenv.2020.107057

Pino, A., Bustamante, W., Escobar, R., & Pino, F. E. (2012). Thermal and lighting behavior of office buildings in Santiago of Chile. Energy and Buildings, 47, 441–449. https://doi.org/10.1016/j.enbuild.2011.12.016

Rana, M. J., Hasan, M. R., Sobuz, M. H. R., & Tam, V. W. Y. (2022). Impact assessment of window-to-wall ratio on energy consumption of an office building of subtropical monsoon climatic country Bangladesh. International Journal of Construction Management, 22(13), 2528–2553. https://doi.org/10.1080/15623599.2020.1808561

Reyes-Barajas, K. D., Romero-Moreno, R. A., Sotelo-Salas, C., Luna-León, A., & Bojórquez-Morales, G. (2020). Passive strategies for energy-efficient building envelopes for housing developments in hot arid climates. WIT Transactions on Ecology and the Environment, 249, 115–125. https://doi.org/10.2495/SC200101

Santamouris, M. (2014). Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy, 103, 682–703. https://doi.org/10.1016/j.solener.2012.07.003

Santamouris, M., & Vasilakopoulou, K. (2021). Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation. e-Prime, 1, 100002. https://doi.org/10.1016/j.prime.2021.100002

Shadram, F., & Mukkavaara, J. (2019). Exploring the effects of several energy efficiency measures on the embodied/operational energy trade-off: A case study of Swedish residential buildings. Energy and Buildings, 183, 283–296. https://doi.org/10.1016/j.enbuild.2018.11.026

Synnefa, A., Saliari, M., & Santamouris, M. (2012). Experimental and numerical assessment of the impact of increased roof reflectance on a school building in Athens. Energy and Buildings, 55, 7–15. https://doi.org/10.1016/j.enbuild.2012.01.044

Vakilinezhad, R. (2023). Energy and thermal analysis of DSF in the retrofit design of office buildings in hot climates. Architectural Engineering and Design Management, 19(6), 642–664. https://doi.org/10.1080/17452007.2022.2147898

Wang, J., Liu, S., Meng, X., Gao, W., & Yuan, J. (2021). Application of retro-reflective materials in urban buildings: A comprehensive review. Energy and Buildings, 247, 111137. https://doi.org/10.1016/j.enbuild.2021.111137

Wang, R., Lu, S., & Feng, W. (2020). A three-stage optimization methodology for envelope design of passive house considering energy demand, thermal comfort and cost. Energy, 192, 116723. https://doi.org/10.1016/j.energy.2019.116723

Xamán, J., Pérez-Nucamendi, C., Arce, J., Hinojosa, J., & Álvarez, G. (2014). Thermal analysis for a double pane window with a solar control film for use in cold and warm climates. Energy and Buildings, 76, 429–439. https://doi.org/10.1016/j.enbuild.2014.03.015

Xue, P., Li, Q., Xie, J., Zhao, M., & Liu, J. (2019). Optimization of window-to-wall ratio with sunshades in China's low-latitude region considering daylighting and energy saving requirements. Applied Energy, 233–234, 62–70. https://doi.org/10.1016/j.apenergy.2018.10.027

Yeom, S., Kim, H., Hong, T., & Lee, M. (2020). Determining the optimal window size of office buildings considering the workers' task performance and the building's energy consumption. Building and Environment, 177, 106872. https://doi.org/10.1016/j.buildenv.2020.106872

Zhou, Y., & Zheng, S. (2020). Machine-learning based hybrid demand-side controller for high-rise office buildings with high energy flexibilities. Applied Energy, 262, 114416. https://doi.org/10.1016/j.apenergy.2019.114416

HOW TO CITE THIS ARTICLE

Moeini,M , Shaabanian,M , Saeidipour,S and Moradi,Z. (2025). Energy Consumption of Contemporary Office Buildings Based on Envelope Materials and Building Dimensions: A Simulation-Based Study in a Semi-Arid Climate (Case Study: Tehran City, Iran)(e735602). International Journal of Urban Management and Energy Sustainability, 7(1), e735602

DOI:10.22034/ijumes.2025.735602