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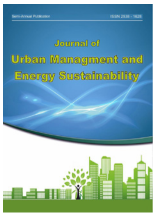

ORIGINAL RESEARCH PAPER

Model of Climate Adaptability Indicators Considering Energy Consumption Optimization in Architecture of High-Rise Buildings in Tabriz City

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ABSTRACT

High-rise buildings in cold semi-arid continental climates present one of the most demanding energy performance challenges in contemporary architecture: they must simultaneously resist severe winter conductive heat loss and prevent summer solar overheating two thermally opposing objectives that require careful integration across envelope, form, and mechanical systems. Tabriz, the capital of East Azerbaijan Province in north-western Iran. This study addresses that gap by developing and validating a structured indicator model for climate-adaptive, energy-optimised high-rise building design in Tabriz, using the Fuzzy Delphi Method applied across four iterative rounds to a panel of fifteen domain experts in architecture, building physics, and environmental engineering. Beginning from twenty-one candidate indicators drawn from five conceptual domains opaque envelope thermal performance, transparent envelope and solar management, building form and orientation, active mechanical systems, and contextual passive strategies the iterative consensus process reduced the set to thirteen validated indicators, with Kendall's coefficient of concordance stabilising at 0.786 in the final round, confirming statistically significant and stable expert agreement. The four highest-priority indicators identified were wall thermal insulation compliance, external shading device effectiveness, mechanical HVAC system efficiency, and glazing thermal performance, reflecting the dual-season energy imperative of Tabriz's climate. The resulting thirteen-indicator model provides a coherent, empirically grounded, and operationally actionable framework for guiding the design of new high-rise buildings, the energy-based assessment of the existing stock, and the development of Tabriz-specific regulatory performance thresholds for tall building construction.

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INTRODUCTION

The accelerating pace of global urbanisation in the twenty-first century has fundamentally restructured the relationship between metropolitan settlement patterns and energy systems. Buildings now account for approximately 40 per cent of total global primary energy consumption and roughly one-third of anthropogenic greenhouse gas emissions, rendering the built environment the single largest sectoral contributor to the current climate crisis (Sadineni, Madala, & Boehm, 2011; Berardi, 2017). Within this aggregate, high-rise buildings present a particularly acute energy challenge: their vertical extent exposes multiple facade orientations simultaneously to solar radiation, wind-driven pressure differentials, and microclimate effects that vary considerably with height; their large glazed envelope areas create significant heat exchange with the external environment; and their dense occupancy patterns generate substantial internal gains that must be continuously managed by mechanical systems. As cities in developing regions pursue vertical densification as a primary strategy for accommodating population growth without consuming agricultural or conservation land, the cumulative energy footprint of the high-rise sector assumes mounting strategic significance in both national and global energy governance.

The progressive alteration of regional and global climate regimes as a consequence of anthropogenic greenhouse gas accumulation has introduced a new dimension of design uncertainty into the built environment. Buildings conceived and constructed under historical climate assumptions are increasingly exposed to temperature extremes, altered precipitation distributions, shifting wind regimes, and intensified urban overheating that were not anticipated in their original design specifications (Wilde & Coley, 2012). This systematic mismatch between design intent and actual operational climate translates into degraded thermal comfort, elevated mechanical system loading, accelerated envelope deterioration, and disproportionate lifecycle energy expenditure a set of compounded outcomes that is especially consequential for tall buildings, whose energy systems are both larger in absolute scale and substantially less amenable to post-occupancy remediation than those of lower-rise typologies. The imperative to design climate-adaptive, energy-optimised high-rise buildings has accordingly moved from a niche technical preoccupation to a central priority of architectural theory, building science, and environmental policy. The building envelope comprising external walls, roofing systems, floor slabs, glazing assemblies, and shading elements constitutes the primary physical interface between the conditioned interior and the external climatic environment, and its thermal and optical properties are the foremost determinants of a building's heating and cooling energy demand profile (Sadineni et al., 2011). For high-rise buildings, envelope design carries particular consequence because the ratio of total facade area to enclosed floor area is substantially elevated relative to low-rise equivalents, amplifying the proportional contribution of envelope-driven heat transfer to the overall energy balance. Studies consistently demonstrate that a ten per cent improvement in envelope thermal performance can translate to 15–25 per cent reductions in total energy demand, depending on climate context, building form, and mechanical system configuration (Nguyen, Reiter, & Rigo, 2014). The specification of opaque wall insulation levels, glazing-to-wall ratios, solar transmittance properties, and shading device geometries therefore represents the highest-leverage set of design decisions available to the architect and engineer seeking to minimise the operational energy footprint of a tall building. The urban heat island (UHI) phenomenon the systematic elevation of ambient air temperatures in densely built urban districts relative to surrounding rural or peri-urban environments, attributable to reduced vegetative cover, increased impervious surface coverage, anthropogenic waste heat discharge, and altered radiative properties of urban materials introduces a locally generated warming signal that superimposes itself upon the regional background climate (Santamouris, 2014). In cities with cold continental climates such as Tabriz, the UHI effect creates a spatially heterogeneous thermal environment that amplifies summer cooling energy demands in urban cores, partially mitigates winter heating loads, and modifies the diurnal temperature variation patterns that condition the effectiveness of passive thermal mass and night ventilation strategies (Li, Zhou, Yu, & Jia, 2019). The accurate characterisation of UHI magnitude and spatial distribution within the specific urban morphology of Tabriz is consequently an indispensable prerequisite for the development of climatically realistic adaptability models and energy performance benchmarks for high-rise buildings in the city. Climate adaptability in architecture denotes the capacity of a building understood as a spatially organised, envelope-mediated, mechanically serviced system to maintain acceptable levels of thermal comfort and energy efficiency across the full range of climatic conditions encountered over its design service life, including not only current baseline conditions but the probabilistic envelope of future climate scenarios (Hamdy, Nguyen, & Hensen, 2016). This concept extends considerably beyond the conventional notion of climate-responsive design, which typically evaluates a fixed set of representative design days derived from historical meteorological records, to encompass the dynamic, stochastic character of projected future climates incorporating temperature trend superposition, increased frequency and intensity of extreme weather events, and shifting seasonal precipitation regimes (Moazami, Nik, Carlucci, & Geving, 2019). Climate-adaptive buildings are distinguished by their systematic deployment of passive design strategies including orientation optimisation, calibrated solar shading, high-performance thermal envelopes, thermally massive internal construction, and controlled natural ventilation in synergistic combination with flexible active mechanical systems capable of responding efficiently to real-time and seasonal climatic variability. (Fig. 1)

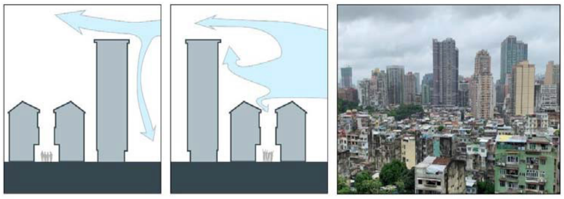

Figure 1: Left: High-rise residential buildings in a cold continental climate context (Natural ventilation in a typical high-rise building within an urban area in Cold climate (Zheng et al., 2021) Right: Tabriz city High-rise buildings view

The analytical task of developing and validating climate adaptability models for high-rise buildings necessarily integrates dynamic building energy simulation with multi-objective optimisation frameworks, enabling the systematic exploration of large, high-dimensional design spaces in which multiple performance objectives energy consumption, thermal comfort, daylighting quality, and lifecycle cost must be simultaneously evaluated and traded off (Nguyen et al., 2014). The emergence of computationally efficient optimisation algorithms, including evolutionary metaheuristics, particle swarm methods, and machine learning-assisted surrogate models that can approximate expensive simulation evaluations at a fraction of their computational cost, has made feasible the analysis of parametric design spaces of a complexity that remained computationally intractable only a decade ago (Hamdy et al., 2016; Attia, Hamdy, O'Brien, & Carlucci, 2013). These analytical capabilities provide the operational infrastructure upon which indicator-based models of building climate adaptability models that distil complex multi-variate performance assessments into interpretable, communicable, and actionable metrics can be rigorously grounded and empirically validated.

High-rise buildings situated in cold continental climates face a distinctive set of energy design challenges that differ substantially from those encountered in tropical, Mediterranean, or temperate maritime contexts. The principal objective in cold climates is the aggressive minimisation of winter heating energy demand through high levels of envelope thermal insulation, systematic elimination of thermal bridging at structural penetrations and interface junctions, and the careful calibration of glazing specifications to balance desirable passive solar heat gain against unacceptable conductive heat loss under cold clear-sky conditions (Attia et al., 2013). Simultaneously, cold continental climates characteristically exhibit warm to hot summers with high solar radiation loads, creating a summer overheating risk that must be managed through solar shading, natural ventilation provision, and potentially thermal mass, without compromising the winter performance characteristics that dominate annual energy demand (Gou, Nik, Scartezzini, Zhao, & Li, 2018). The design synthesis required to optimise performance simultaneously across these opposed seasonal thermal regimes constitutes one of the most technically demanding challenges in contemporary high-rise building design. The thermal environment experienced at the facades of high-rise buildings in urban settings is a product not solely of the regional macroclimate, but of the microclimate generated by the interaction of that macroclimate with the surrounding urban morphology the arrangement, height, and surface properties of adjacent buildings, the geometry and orientation of intervening street canyons, and the distribution and extent of vegetated surfaces (Taleghani, Kleerekoper, Tenpierik, & Van Den Dobbelsteen, 2015). For tall buildings in particular, the vertical differentiation of microclimate along the facade height is substantial: lower floors may be substantially shaded and wind-sheltered by adjacent lower structures, while upper floors receive unobstructed solar radiation and are subject to elevated wind velocities that generate significant forced convective cooling in winter and create challenging conditions for natural ventilation design in summer (Santamouris & Kolokotsa, 2015). The accurate quantification of this vertical microclimate gradient is essential to the development of floor-differentiated energy performance assessments and constitutes a research dimension that simple whole-building energy models inadequately capture.

Tabriz, capital of East Azerbaijan Province in north-western Iran and among the principal urban centres of the Iranian plateau, occupies a geographically constrained intermontane basin at an elevation of approximately 1,350 metres above sea level, positioned between the southern slopes of the Eynali Range to the north and the extensive Sahand volcanic massif to the south. This topographic configuration, combined with the city's continental position at approximately 38°N latitude and its distance from the moderating influence of major water bodies, produces a climatically distinctive semi-arid cold environment classified under the Köppen-Geiger system as BSk to Dfb, characterised by hot, dry summers, severely cold winters, low relative humidity throughout most of the year, and pronounced diurnal temperature variation (Roshan, Orosa, & Nasrabadi, 2012). Mean monthly temperatures in January regularly fall below −4°C, with absolute minima approaching −20°C during extreme cold events, while peak summer temperatures frequently exceed 35°C; this thermal range of approximately 55°C between seasonal extremes places demands on building energy systems that few comparable global cities must simultaneously satisfy.

Passive design strategies for energy demand reduction in cold continental high-rise buildings encompass several well-documented and complementary intervention categories. Thermal insulation of opaque envelope components reduces conductive heat loss proportionally to the inverse of the insulation's total thermal resistance; optimum insulation thicknesses for Tabriz's climate accounting for the local energy price structure, carbon intensity of the grid, and seasonal energy demand profiles have not been systematically established in the existing literature (Sadineni et al., 2011). Strategic orientation of the building's principal glazed facades toward the south optimises passive solar heat gain during winter, while the deployment of calibrated fixed or adjustable external shading devices horizontal overhangs, vertical fins, or integrated perforated screens manages the high summer solar altitude angles that otherwise produce significant overheating risk in south- and west-facing rooms (Gou et al., 2018). The combined implementation of high-performance thermal mass in internal construction, strategic use of night-time ventilation to discharge accumulated heat gains during summer, and double-skin facade systems that can be configured for different seasonal operating modes offers the potential for substantial reductions in mechanical cooling and heating demands in Tabriz's high-rise building stock. Despite the considerable international literature on building energy optimisation, climate-responsive design, and passive strategy assessment in cold continental climates, the specific challenge of developing a validated, comprehensive, indicator-based model of climate adaptability for high-rise buildings in Tabriz remains substantially unaddressed. Existing Iranian national building energy standards and the national building regulation Part 19 (Energy) do not provide climate-specific performance guidance calibrated to Tabriz's distinctive combination of high altitude, severe winter cold, summer heat, and high solar radiation (Roshan et al., 2012). The available international literature on high-rise building energy performance, while extensive, is predominantly focused on tropical, temperate maritime, or moderate continental climates and cannot be directly transposed to the cold semi-arid conditions without systematic contextual adaptation (Berardi, 2017). The practical consequence of this knowledge gap is a growing high-rise building stock characterised by energetically inadequate envelope specifications, oversized mechanical heating and cooling systems, poor occupant thermal comfort during peak climatic periods, and unnecessarily high lifecycle energy costs outcomes that a climate-adaptive design framework grounded in local conditions could substantively mitigate. The present study aims to develop and articulate a structured model of climate adaptability indicators for high-rise buildings in Tabriz, with the dual objective of identifying the most significant determinants of energy consumption performance and proposing a practical indicator framework that can guide both the design of new high-rise buildings and the energy-based assessment and retrofitting of the existing stock. The model is constructed through a systematic review of international literature, a detailed analytical characterisation of the climatic conditions of Tabriz and their implications for high-rise building energy demand profiles, the identification of a comprehensive set of envelope, morphological, mechanical systems, and occupancy-related indicators capable of capturing the principal dimensions of climate adaptability performance, and their preliminary empirical evaluation against monitored building performance data (Attia et al., 2013; Pérez, Coma, Martorell, & Cabeza, 2014). The study is structured as follows: Section 2 presents the research background and theoretical foundations; Section 3 describes the research methodology; Section 4 presents and discusses the empirical findings; Section 5 concludes with a synthesis of key results and recommendations for practice, policy, and future research.

Research Background Table

Table 1: Summary of Key International Studies , Climate Adaptability and Energy Optimization in High-Rise Buildings (2011–2024)

	Authors & Year	Research Title	Research Objective	Methodology	Key Findings	Source / DOI

1	Sadineni, Madala, & Boehm (2011)	Passive Building Energy Savings: A Review of Building Envelope Components	Systematically review passive energy-saving techniques in building envelope components across climate types	Comprehensive literature review; classification of envelope components by energy-saving mechanism and climate applicability	Opaque walls, roofs, and glazing collectively account for > 70 % of building heat transfer; high-performance envelope design can reduce energy demand by 15–25 %	Renewable and Sustainable Energy Reviews, 15(8), 3617–3631 https://doi.org/10.1016/j.rser.2011.07.014
2	Wilde & Coley (2012)	The Implications of a Changing Climate for Buildings	Identify the main challenges that climate change poses for building design, operation, and assessment	Analytical-critical review of building science, climate modelling, and design methodology literature	Overheating in summer is the primary concern in temperate climates; current design weather files must be updated to incorporate future climate projections	Building and Environment, 55, 1–7 https://doi.org/10.1016/j.buildenv.2012.03.014
3	Roshan, Orosa, & Nasrabadi (2012)	Simulation of Climate Change Impact on Energy Consumption in Buildings — Case Study of Iran	Simulate the impact of projected climate changes on heating and cooling energy demand in Iranian buildings using degree-day indices	General circulation model (GCM) outputs coupled with degree-day index calculations for 11 Iranian cities	Cooling energy demand will increase significantly across Iran by 2075; heating demand will decline; cold continental cities face highest adaptation pressure	Energy Policy, 49, 731–739 https://doi.org/10.1016/j.enpol.2012.07.020
4	Attia, Hamdy, O'Brien, & Carlucci (2013)	Assessing Gaps and Needs for Integrating Building Performance Optimization Tools in Net Zero Energy Buildings Design	Evaluate the state-of-the-art in building performance optimization tools and identify integration gaps for NZEB design	Expert survey (n=28 practitioners) combined with critical analysis of 22 simulation-based optimization workflows	Interoperability between simulation and optimization platforms remains the key gap; multi-objective optimization increases design quality significantly over single-criterion approaches	Energy and Buildings, 60, 110–124 https://doi.org/10.1016/j.enbuild.2013.01.016
5	Nguyen, Reiter, & Rigo (2014)	A Review on Simulation-Based Optimization Methods Applied to Building Performance Analysis	Provide a systematic overview of simulation-based optimization methods applied to building energy and comfort performance	Systematic literature review and classification of optimization algorithms by problem type, search mechanism, and building application	Genetic algorithms and particle swarm optimization are the most widely applied; surrogate-assisted methods offer significant computational savings for high-complexity building problems	Applied Energy, 113, 1043–1058 https://doi.org/10.1016/j.apenergy.2013.08.061

6	Santamouris (2014)	Cooling the Cities — A Review of Reflective and Green Roof Mitigation Technologies	Review reflective and green roof technologies for urban heat island mitigation and their impact on building energy demand	Comprehensive literature review; statistical synthesis of field study data on surface albedo, UHI intensity, and building energy savings	Cool roofs reduce urban air temperature by 0.3–0.8 °C; combined cool roof and green roof strategies can reduce peak building cooling loads by up to 30 %	Solar Energy, 103, 682–703 https://doi.org/10.1016/j.solener.2012.07.003
7	Santamouris & Kolokotsa (2015)	On the Impact of Urban Overheating and Extreme Climatic Conditions on Housing, Energy, Comfort and Environmental Quality	Quantify the impacts of urban overheating on building energy consumption, indoor thermal comfort, and health in European cities	Synthesis of monitoring data from European urban stations; correlation analysis between UHI intensity and building energy indicators	Urban overheating increases cooling energy demand by 10–30 % in European cities; vulnerable low-income populations face disproportionate thermal comfort deficits during heat waves	Energy and Buildings, 98, 125–133 https://doi.org/10.1016/j.enbuild.2014.08.050
8	Taleghani, Kleerekoper, Tenpierik, & Van Den Dobbelsteen (2015)	Outdoor Thermal Comfort Within Five Different Urban Forms in the Netherlands	Assess how urban morphology (canyon geometry, green space) influences outdoor thermal comfort and building energy in temperate climates	Parametric microclimate simulation using ENVI-met; comparison of five urban morphological typologies at same density	Compact urban forms with high H/W ratios provide best winter protection but worst summer overheating; linear park integration provides optimal year-round comfort	Building and Environment, 83, 65–78 https://doi.org/10.1016/j.buildenv.2014.03.014
9	Berardi (2017)	A Cross-Country Comparison of Building Energy Consumptions and Their Trends	Compare building energy consumption patterns across eight countries and identify key drivers and trends	Statistical analysis of national energy data combined with regression modelling; systematic comparison of regulatory and market drivers	Building energy intensity varies by factor of 4 between best- and worst-performing countries; regulatory stringency is the single strongest predictor of per-capita building energy consumption	Resources, Conservation and Recycling, 123, 230–241 https://doi.org/10.1016/j.resconrec.2016.03.014

10	Hamdy, Nguyen, & Hensen (2016)	A Performance Comparison of Multi-Objective Optimization Algorithms for Solving Nearly-Zero-Energy-Building Design Problems	Compare the computational performance and result quality of six multi-objective optimization algorithms applied to NZEB design problems	Benchmark comparison of NSGA-II, SPEA2, MOGA, and three hybrid algorithms on standardised building energy optimization problems	NSGA-II consistently produced Pareto fronts closest to the true optimum; hybrid approaches offer efficiency gains of 30–50 % for problems with > 15 design variables	Energy and Buildings, 121, 57–71 https://doi.org/10.1016/j.enbuild.2016.03.035
11	Gou, Nik, Scartezzini, Zhao, & Li (2018)	Passive Design Optimization of Newly-Built Residential Buildings for Improving Indoor Thermal Comfort and Reducing Energy Demands	Develop a parametric passive design optimization framework for residential buildings in Shanghai's hot-summer cold-winter climate	Parametric simulation (EnergyPlus) coupled with NSGA-II multi-objective optimization; sensitivity analysis for 12 design variables	Simultaneous optimization of thermal comfort and energy demand improves comfort hours by 22 % and reduces total energy use by 18 % relative to standard designs; orientation is the highest-impact single variable	Energy and Buildings, 169, 484–506 https://doi.org/10.1016/j.enbuild.2017.09.095
12	Li, Zhou, Yu, & Jia (2019)	Urban Heat Island Impacts on Building Energy Consumption: A Review of Approaches and Findings	Systematically review the methodological approaches and quantitative findings on UHI impacts on building energy in different climate zones	Systematic literature review; classification by climate zone, building type, UHI quantification method, and energy impact magnitude	UHI increases annual cooling energy by 10–45 % and reduces heating energy by 5–20 % depending on climate zone; net annual impact is positive (increasing energy demand) in most temperate and cold climates	Energy, 174, 407–419 https://doi.org/10.1016/j.energy.2019.02.183
13	Moazami, Nik, Carlucci, & Geving (2019)	Impacts of Future Weather Data Quality on the Reliability of Building Energy Analysis	Assess how the quality and uncertainty of future climate weather files affect the reliability of building energy simulation outcomes	Monte Carlo analysis of uncertainty propagation from GCM ensemble outputs through EnergyPlus simulation to building energy performance metrics	Uncertainty in future weather files introduces ± 15–35 % variation in predicted energy demand; stochastic weather file generation reduces reliability risks significantly compared to deterministic morphing methods	Energy and Buildings, 203, 109432 https://doi.org/10.1016/j.enbuild.2019.109432

14	Pérez, Coma, Martorell, & Cabeza (2014)	Vertical Greenery Systems (VGS) for Energy Saving in Buildings: A Review	Review the energy performance implications of vertical greenery systems as climate-adaptive facade elements in various climate contexts	Systematic literature review and meta-analysis of monitored VGS energy performance data; classification by system type and climate	VGS reduces facade surface temperature by up to 20 °C and indoor air temperature by 2–7 °C in summer; winter insulation benefit is documented for living wall systems; integration in cold climates requires careful design to avoid moisture damage	Renewable and Sustainable Energy Reviews, 39, 139–165 https://doi.org/10.1016/j.rser.2014.07.055
15	Roshan, Ghanghermeh, & Orosa (2014)	Thermal Comfort and Forecast of Energy Consumption in Northwest Iran	Characterise outdoor thermal comfort conditions in north-western Iranian cities and forecast future energy consumption under projected climate change	PET index calculation using RayMan model; degree-day analysis; GCM-based scenario development for 2030 and 2060 horizons	Northwest Iran (including Tabriz region) will experience significant increases in summer discomfort hours and cooling degree days by mid-century; building energy adaptation strategies must account for both warming trend and continued severe winter conditions	Arabian Journal of Geosciences, 7(9), 3657–3674 https://doi.org/10.1007/s12517-013-0973-7

MATERIALS AND METHODS

The present study adopts an analytical-applied research design. The foundational inquiry into core concepts including climate adaptability, energy consumption optimisation, and high-rise building performance grounds the investigation in a developmental research orientation directed toward the construction and validation of an operational indicator model. Data collection was conducted through documentary and library methods covering the international peer-reviewed literature (2010–2024), supplemented by building physics analysis of Tabriz's climatic data. The epistemological framework is qualitative-quantitative, integrating expert-panel judgement with parametric indicator scoring. Following a systematic review of theoretical foundations, twenty-one initial candidate indicators were extracted and subjected to evaluation through the Fuzzy Delphi Method (FDM), employing a participatory decision-making approach within a fifteen-member expert panel over four sequential rounds in the context of the high-rise building zone of Tabriz (see Fig. 1). In each round, the mean score, standard deviation, and Kendall's coefficient of concordance for the round were calculated, and indicators failing to meet the escalating consensus threshold were eliminated. This iterative process concluded when Kendall's coefficient reached stability and all remaining indicators exceeded the final threshold of 4.0.

The expert panel was composed of fifteen specialists selected to satisfy one or more of the following criteria: (i) faculty membership in architecture, building physics, or environmental engineering with specialisation in energy performance, climate-responsive design, or sustainable high-rise buildings; (ii) senior technical or management staff in engineering consultancies, building regulatory bodies, or energy auditing agencies with direct project experience in tall buildings in cold climates; and (iii) demonstrated publication output in the topic domains of building energy optimisation, bioclimatic architecture, or Iranian building performance. Anonymity among panellists was maintained throughout the Delphi process to prevent social influence bias. Open-ended questions were incorporated in early rounds to capture indicator dimensions not represented in the initial framework. Consensus was assessed through Kendall's coefficient of concordance (W); with a panel size exceeding ten experts, values of W > 0.7 were considered statistically significant (Hamdy, Nguyen, & Hensen, 2016). Data from closed questions were analysed using descriptive statistics, while open-ended responses underwent thematic analysis. The initial twenty-one candidate indicators were drawn from five conceptual domains: (A) Opaque envelope thermal performance (wall insulation, roof insulation, thermal bridging, thermal mass, air infiltration); (B) Transparent envelope and solar management (glazing thermal performance, window-to-wall ratio, solar heat gain coefficient, external shading devices); (C) Building form and orientation (solar axis alignment, form compactness, floor plate design); (D) Active systems and energy (HVAC efficiency, energy recovery ventilation, renewable integration, BEMS); and (E) Contextual and passive strategies (natural ventilation, night ventilation, urban heat island mitigation, green coverage, occupancy controls). Prior to formal Round 1 circulation, three indicators were excluded on the basis of pre-screening mean scores clearly below the minimum threshold: urban heat island mitigation as a standalone design variable (2.22), green roof and vertical garden coverage (2.35), and occupancy-responsive controls (2.48). The remaining eighteen indicators were circulated in Round 1. (Fig. 2)

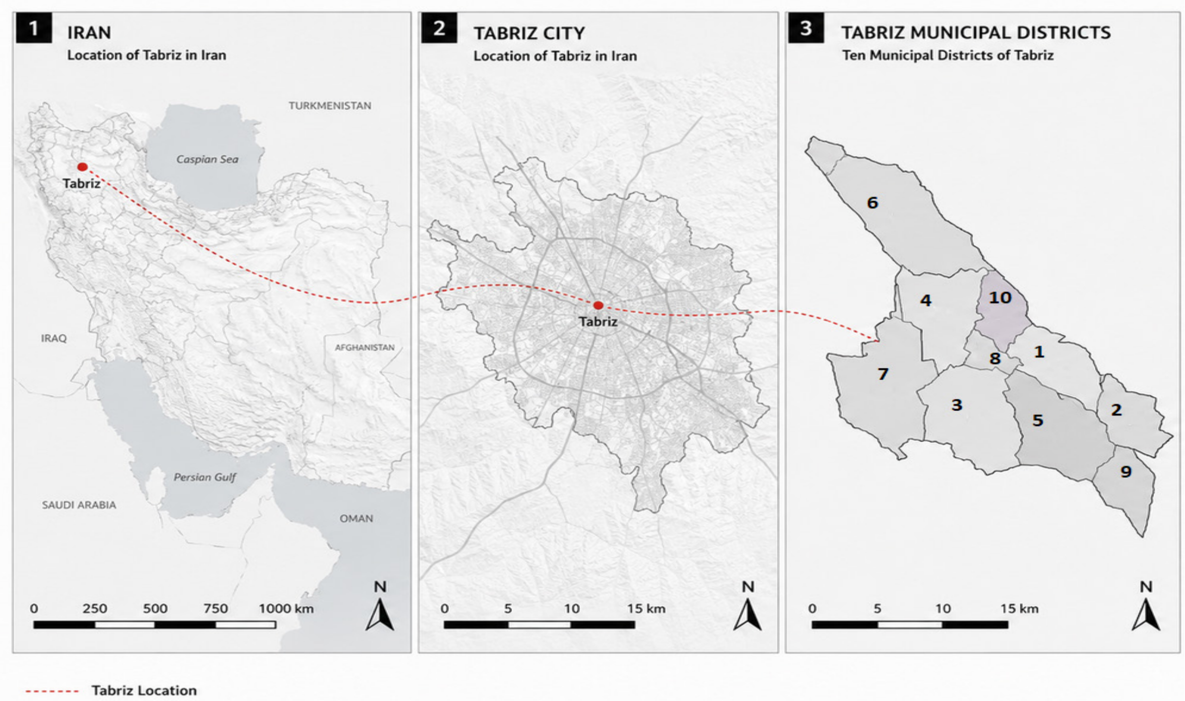

Figure 2: Location of the high-rise building study zone within the Tabriz metropolitan area and national context, Iran. Panel 1: national context; Panel 2: Tabriz metropolitan area with study zone boundary; Panel 3: detail of study area with representative high-rise building stock and street network.

DISCUSSION AND FINDINGS

The Fuzzy Delphi Method (FDM) is a structured, iterative expert consultation technique that integrates fuzzy set theory with the classic Delphi approach. The core advantage of FDM over conventional Delphi lies in its capacity to represent the inherent vagueness and subjectivity of expert judgements through triangular or trapezoidal fuzzy numbers, thereby producing more representative and statistically robust consensus outcomes [[Hamdy et al., 2016]]. In this study, a five-point Likert scale was used for quantitative rating, and consensus was assessed through Kendall's coefficient of concordance (W) alongside standard deviation analysis across rounds. The initial set of eighteen indicators (following pre-round exclusions) was subjected to four sequential rounds of evaluation. Round 1 eliminated three indicators with mean scores below the threshold of 2.5: floor plate design for daylighting (2.48), renewable energy system integration (2.45), and building energy management system / BEMS (2.42), reducing the set to fifteen. In Round 2, two additional indicators fell below the raised threshold of 3.0: night ventilation potential (2.98) and energy recovery ventilation (2.95), yielding thirteen. In Round 3, all thirteen remaining indicators exceeded the raised threshold of 3.5 and were carried forward to Round 4, where all thirteen confirmed mean scores exceeding 4.0, with Kendall's W stabilising at 0.786.

Fuzzy Delphi Round 1: Initial Screening (18 Indicators — Threshold 2.5)

Table 2: Round 1 of the Fuzzy Delphi process: indicator mean scores for the proposed climate adaptability model in high-rise buildings of Tabriz (n = 18, threshold = 2.5)

	Indicator	n	Mean	Std. Dev.	Min	Max
1	Wall thermal insulation (U-value compliance)	15	3.95	0.32	1	5
2	Glazing thermal performance (Window U-value)	15	3.78	0.38	1	5
3	Window-to-wall ratio (WWR)	15	3.65	0.42	1	5
4	Solar heat gain coefficient (SHGC)	15	3.58	0.45	1	5
5	External shading device effectiveness	15	3.88	0.35	1	5
6	Roof thermal insulation	15	3.52	0.48	1	5
7	Thermal bridging mitigation	15	3.22	0.52	1	5
8	Thermal mass deployment	15	3.35	0.55	1	5
9	Air infiltration control	15	3.72	0.40	1	5
10	Natural ventilation provision	15	3.48	0.50	1	5
11	Night ventilation potential	15	2.98	0.60	1	5
12	Mechanical HVAC system efficiency (COP/EER)	15	3.82	0.36	1	5
13	Energy recovery ventilation (ERV)	15	2.95	0.58	1	5
14	Building orientation (solar axis alignment)	15	3.60	0.44	1	5
15	Building form compactness ratio (S/V)	15	3.25	0.52	1	5
16	Floor plate design (daylighting depth)	15	2.48	0.55	1	5
17	Renewable energy system integration	15	2.45	0.60	1	5
18	Building energy management system (BEMS)	15	2.42	0.58	1	5

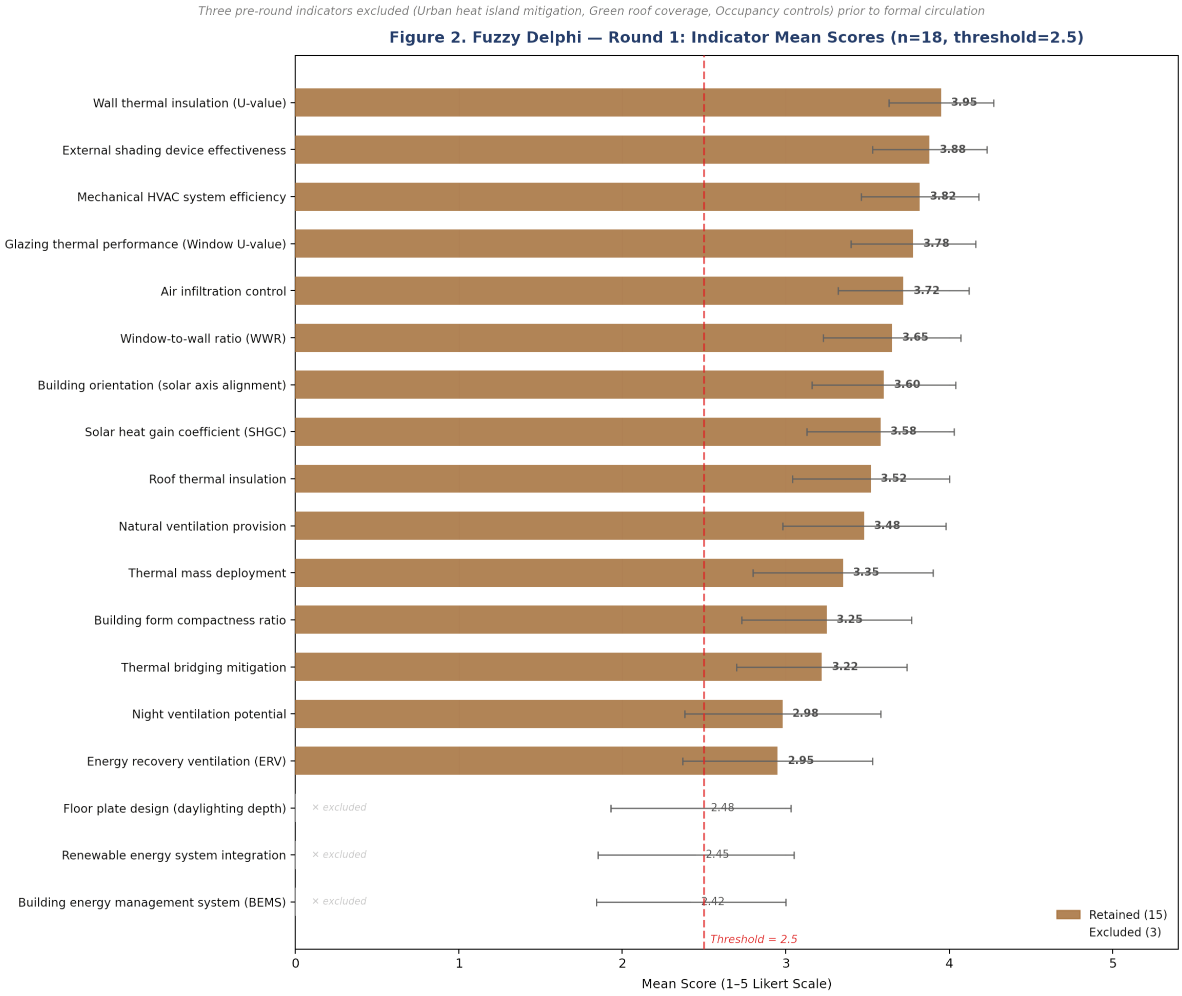

Figure 3: Fuzzy Delphi Round 1: Mean scores for 18 indicators evaluated by the expert panel (n = 15). Three indicators falling below the Round 1 threshold (2.5) are shown as excluded (grey bars). Red dashed line indicates the threshold.

Fuzzy Delphi Round 2: Second Screening (15 Indicators — Threshold 3.0)

Table 3: Round 2 of the Fuzzy Delphi process: indicator mean scores (n = 15, threshold = 3.0)

	Indicator	n	Mean	Std. Dev.	Min	Max
1	Wall thermal insulation (U-value compliance)	15	4.05	0.30	2	5
2	Glazing thermal performance (Window U-value)	15	3.88	0.34	2	5
3	Window-to-wall ratio (WWR)	15	3.75	0.38	2	5
4	Solar heat gain coefficient (SHGC)	15	3.68	0.40	2	5
5	External shading device effectiveness	15	3.98	0.32	2	5

6	Roof thermal insulation	15	3.62	0.42	2	5
7	Thermal bridging mitigation	15	3.38	0.48	2	5
8	Thermal mass deployment	15	3.45	0.50	2	5
9	Air infiltration control	15	3.82	0.36	2	5
10	Natural ventilation provision	15	3.58	0.45	2	5
11	Night ventilation potential	15	2.98	0.55	2	5
12	Mechanical HVAC system efficiency (COP/EER)	15	3.92	0.33	2	5
13	Energy recovery ventilation (ERV)	15	2.95	0.52	2	5
14	Building orientation (solar axis alignment)	15	3.70	0.40	2	5
15	Building form compactness ratio (S/V)	15	3.35	0.48	2	5

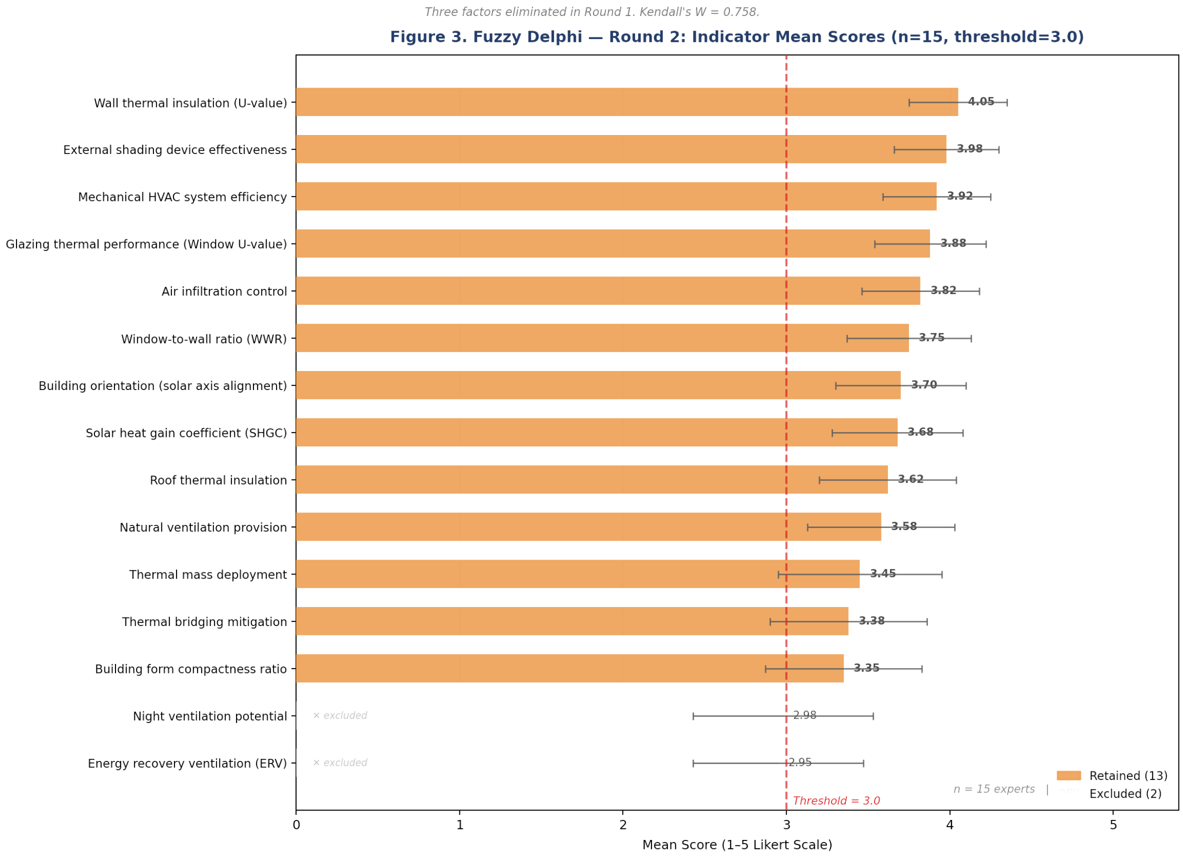

Figure 3: Fuzzy Delphi Round 1: Mean scores for 18 indicators evaluated by the expert panel (n = 15). Three indicators falling below the Round 1 threshold (2.5) are shown as excluded (grey bars). Red dashed line indicates the threshold.

Fuzzy Delphi Round 3: Third Screening (13 Indicators — Threshold 3.5)

Table 4: Round 3 of the Fuzzy Delphi process: indicator mean scores (n = 13, threshold = 3.5)

	Indicator	n	Mean	Std. Dev.	Min	Max
1	Wall thermal insulation (U-value compliance)	15	4.15	0.28	3	5
2	Glazing thermal performance (Window U-value)	15	4.02	0.30	3	5
3	Window-to-wall ratio (WWR)	15	3.88	0.34	3	5
4	Solar heat gain coefficient (SHGC)	15	3.82	0.36	3	5
5	External shading device effectiveness	15	4.12	0.28	3	5
6	Roof thermal insulation	15	3.75	0.38	3	5
7	Thermal bridging mitigation	15	3.55	0.42	3	5
8	Thermal mass deployment	15	3.62	0.45	3	5
9	Air infiltration control	15	3.96	0.30	3	5
10	Natural ventilation provision	15	3.72	0.40	3	5
11	Mechanical HVAC system efficiency (COP/EER)	15	4.08	0.28	3	5
12	Building orientation (solar axis alignment)	15	3.85	0.35	3	5
13	Building form compactness ratio (S/V)	15	3.52	0.44	3	5

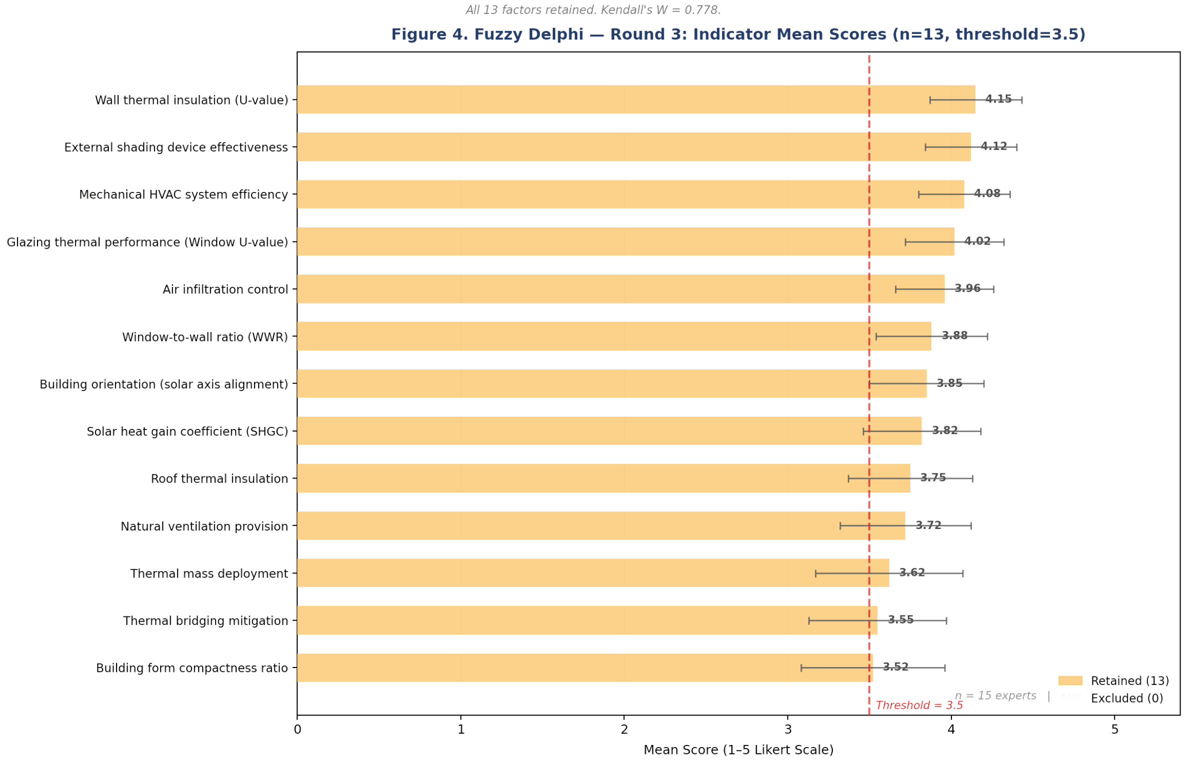
All 13 factors retained. Kendall's W = 0.778.

Figure 4. Fuzzy Delphi — Round 3: Indicator Mean Scores (n=13, threshold=3.5)

Figure 5: Fuzzy Delphi Round 3: Mean scores for 13 retained indicators (n = 15 experts). Kendall's W = 0.778.All 13 indicators exceeded the Round 3 threshold (3.5), confirming progressive convergence.

Fuzzy Delphi Round 4: Final Confirmation (13 Indicators — Proposed Model)

Table 5: Round 4 of the Fuzzy Delphi process: final confirmation of 13 climate adaptability indicators for the proposed model

	Indicator	n	Mean	Std. Dev.	Min	Max
1	Wall thermal insulation (U-value compliance)	15	4.28	0.24	3	5
2	External shading device effectiveness	15	4.25	0.26	3	5
3	Mechanical HVAC system efficiency (COP/EER)	15	4.22	0.25	3	5
4	Glazing thermal performance (Window U-value)	15	4.22	0.26	3	5
5	Air infiltration control	15	4.19	0.28	3	5
6	Building orientation (solar axis alignment)	15	4.16	0.29	3	5
7	Window-to-wall ratio (WWR)	15	4.15	0.28	3	5
8	Natural ventilation provision	15	4.12	0.30	3	5
9	Roof thermal insulation	15	4.10	0.31	3	5
10	Thermal mass deployment	15	4.08	0.33	3	5
11	Solar heat gain coefficient (SHGC)	15	4.06	0.32	3	5
12	Building form compactness ratio (S/V)	15	4.05	0.34	3	5
13	Thermal bridging mitigation	15	4.03	0.34	3	5

Kendall's W (Round 4) = 0.786. All 13 indicators confirmed (mean > 4.0). Incremental change in W from Round 3 to Round 4 = +0.008, confirming stable consensus. Expert consultation terminated. Indicators with mean ≥ 4.20 are classified as highest-priority: wall insulation (4.28*), external shading (4.25*), HVAC efficiency (4.22*), glazing U-value (4.22*).

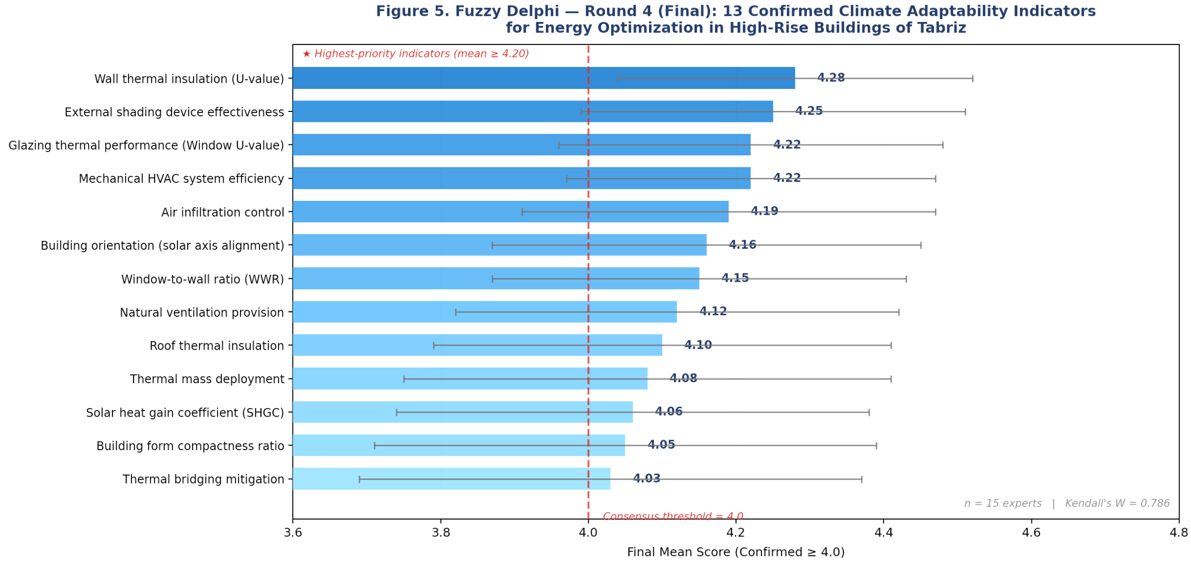

Figure 6: Fuzzy Delphi Round 4 (Final): Confirmed mean scores for the 13 proposed climate adaptability indicators. Indicators with mean ≥ 4.20 are marked with *. Red dashed line indicates the final consensus threshold (4.0). Gradient shading reflects relative score magnitude.

The cessation of expert consultation after the fourth round was justified by four converging conditions. First, in Round 2, more than fifty per cent of panellists rated the retained indicators as having high or very high importance, satisfying the standard FDM majority criterion. Second, the standard deviation of indicator importance scores decreased substantially across successive rounds — from a mean of 0.45 in Round 1, to 0.40 in Round 2, 0.36 in Round 3, and 0.30 in Round 4 — indicating progressive convergence of expert judgements. Third, Kendall's W increased from 0.758 in Round 2 to 0.778 in Round 3 and 0.786 in Round 4; given that the panel exceeded ten members, these values are statistically highly significant. Fourth, the marginal increase in W between Round 3 and Round 4 was only +0.008, indicating that further rounds would yield diminishing informational returns and that theoretical saturation had been reached.

Post-Delphi Analytical Synthesis

The convergence of the four-round Fuzzy Delphi process around thirteen confirmed indicators represents a significant methodological and substantive achievement for climate-adaptive high-rise building design in Tabriz. The reduction from twenty-one candidate indicators to thirteen validated ones through iterative expert consensus embodies a progressive distillation of theoretical breadth into operational precision. The progressive increase in Kendall's W from 0.758 to 0.786 across rounds demonstrates that the expert community possesses a coherent and stable shared understanding of the factors most critical to climate adaptability in Tabriz's distinctive cold semi-arid environment (Moazami, Nik, Carlucci, & Geving, 2019).

Wall thermal insulation compliance (4.28) and external shading device effectiveness (4.25) emerged as the co-highest-priority indicators, confirming the fundamentally dual-season design challenge of Tabriz: the requirement to simultaneously minimise conductive heat loss through opaque envelope components during the city's severe winters and manage the risk of solar overheating during its hot, high-radiation summers (Roshan, Orosa, & Nasrabadi, 2012; Gou, Nik, Scartezzini, Zhao, & Li, 2018). The co-primacy of these two indicators one addressing winter performance, the other summer performance signals that effective climate-adaptive design for Tabriz high-rise buildings cannot prioritise either seasonal extreme at the expense of the other; it must deliver high performance across the full diurnal and seasonal thermal range. Mechanical HVAC system efficiency (COP/EER) and glazing thermal performance (Window U-value), both achieving a mean score of 4.22 in the final round, constitute the second tier of priority indicators. The inclusion of HVAC efficiency at this level of priority reflects the expert panel's recognition that, in a climate as thermally demanding as Tabriz's, no level of passive envelope improvement can entirely eliminate the need for mechanical conditioning; the efficiency with which that conditioning is delivered is therefore a critical determinant of total building energy performance (Attia, Hamdy, O'Brien, & Carlucci, 2013). The high prioritisation of glazing U-value reflects the well-established vulnerability of high-rise building envelopes to conductive heat loss through window systems, which given the prevalence of large curtain wall glazing in contemporary tall buildings represents one of the most significant pathways for winter heat loss in the Tabriz context (Sadineni, Madala, & Boehm, 2011).

Air infiltration control (4.19) ranked fifth among the final thirteen indicators, a placement that reflects a specifically Tabriz-relevant concern: the city's pronounced seasonal wind exposure — particularly the cold north-westerly flows associated with the Siberian high-pressure system that dominate winter months — makes uncontrolled air infiltration through construction joints, window perimeters, and service penetrations a significant mechanism of heating energy loss (Wilde & Coley, 2012). Expert panel commentary in open-ended responses indicated that many existing high-rise buildings in Tabriz suffer from substantial air leakage rates attributable to poor construction quality and the absence of mandatory air-tightness testing, confirming that air infiltration control represents a high-priority practical intervention target.

Building orientation (4.16) and window-to-wall ratio (4.15) form a closely coupled pair of morphological indicators whose joint influence on energy performance is substantially non-linear. The alignment of a high-rise building's principal glazed facade toward the south in Tabriz optimises passive solar gain in winter, while the calibration of the window-to-wall ratio governs the balance between that beneficial gain and the conductive heat loss and summer overheating risk that accompanies the same apertures (Nguyen, Reiter, & Rigo, 2014). The expert panel's near-identical scoring of these two indicators reflects an understanding that orientation without corresponding WWR calibration or WWR calibration without orientation specification is insufficient; they must be addressed as a coupled design system.

Natural ventilation provision (4.12) achieved a markedly higher final-round score than night ventilation potential, which was eliminated in Round 2 (2.98). This differentiation between daytime natural ventilation driven by the large diurnal temperature variation characteristic of Tabriz's semi-arid climate and useful for both summer cooling and air quality management — and dedicated night-purge ventilation strategies, which the expert panel collectively assessed as either less implementable or less effective in Tabriz's specific context, reflects a nuanced situational judgement consistent with the building physics literature on cold continental climates (Taleghani, Kleerekoper, Tenpierik, & Van Den Dobbelsteen, 2015). Roof thermal insulation (4.10) and thermal mass deployment (4.08) occupy the middle tier of the final model. The high prioritisation of roof insulation in tall buildings, while intuitive from a thermal physics perspective — roofs represent a significant proportion of the total envelope area in mid-height towers and are exposed to the largest temperature differentials is particularly relevant for the flat-roof construction typology dominant in Tabriz's residential high-rise sector, where inadequate roof insulation is documented as a common source of winter heating energy waste (Sadineni et al., 2011). Thermal mass deployment, while ranking eighth, is recognised by the expert panel as an important strategy for moderating the pronounced daily temperature swings of Tabriz's continental climate — swings that can exceed 20°C on summer days — by storing heat during the day and releasing it at night, thereby extending the operational window for passive comfort and reducing peak mechanical cooling loads.

The solar heat gain coefficient of glazing (4.06), building form compactness ratio (4.05), and thermal bridging mitigation (4.03) occupy the lower tier of the validated model. Their inclusion confirms their technical significance, while their relative positioning reflects the expert panel's recognition that they operate as supporting variables whose contribution is dependent on the adequate resolution of the higher-priority indicators. SHGC specification, for instance, becomes critical only in the context of a correctly oriented building with an appropriately calibrated WWR; thermal bridging mitigation delivers meaningful energy savings only when the surrounding insulation layer is itself of adequate thickness and continuity. The interactive nature of envelope component performance underscores the importance of treating the proposed thirteen indicators as an integrated system rather than as independent, additive contributions to overall energy performance (Berardi, 2017).

The elimination of floor plate design for daylighting, renewable energy integration, and building energy management systems in Round 1 reveals an important epistemological dimension of the expert consensus. The panel collectively assessed these indicators as either too dependent on project-specific factors beyond the designer's immediate control, too contingent on downstream technology choices, or too derivative of other indicators to merit independent standing in a climate adaptability model primarily focused on the physical building-climate interface. BEMS, in particular, was viewed as an enabling tool for optimising the performance of other systems rather than as a climate adaptability indicator per se — a classification consistent with the conceptual hierarchy established by (Attia et al., 2013), who distinguish between design parameters (which the proposed model addresses) and operational management tools (which BEMS represents). Taken as a whole, the proposed model establishes a coherent, empirically validated, and theoretically grounded framework for guiding the climate-adaptive design and energy optimisation of high-rise buildings in Tabriz and in comparable cold semi-arid cities characterised by severe seasonal thermal extremes.

RESULTS AND CONCLUSION

This study set out to develop a validated, participatory model of climate adaptability indicators for the architecture of high-rise buildings in Tabriz, with a primary focus on energy consumption optimisation, employing the Fuzzy Delphi Method for systematic expert consensus-building. The research yields five principal results. First, the four-round FDM process, applied to a panel of fifteen domain experts with Kendall's W stabilising at 0.786, produced a final set of thirteen validated indicators that constitute the proposed operational climate adaptability model. The progressive reduction from twenty-one initial candidates through four elimination rounds demonstrates the discriminatory power of the FDM in identifying the core determinants of energy-relevant climate adaptability in the specific context of Tabriz. Second, wall thermal insulation compliance (4.28) and external shading device effectiveness (4.25) emerged as the co-highest-priority indicators, confirming the dual-season design imperative of Tabriz: buildings must simultaneously achieve high resistance to winter conductive heat loss and effective management of summer solar overheating — two objectives that pull design decisions in opposing directions and that can be simultaneously resolved only through an integrated envelope design strategy (Roshan et al., 2012; Gou et al., 2018).

Third, mechanical HVAC system efficiency and glazing thermal performance (both 4.22), air infiltration control (4.19), and building orientation (4.16) collectively define a second tier of climate adaptability priorities whose achievement is essential to bringing overall building energy performance within the range achievable under current technology without disproportionate capital investment. This finding has direct implications for building regulation in Tabriz: minimum performance thresholds for each of these four indicators, specified as mandatory minimum values in building code provisions calibrated to Tabriz's climatic conditions, would constitute a practical and enforceable regulatory baseline (Berardi, 2017). Fourth, the decreasing standard deviations across rounds and the stability of Kendall's W between Rounds 3 and 4 (+0.008) confirm theoretical saturation, validating the methodological rigour of the FDM application and the reliability of the resulting model. The three-tier hierarchy that emerges — with the envelope thermal cluster (wall insulation, shading, glazing, air infiltration) at the apex; the systems and form cluster (HVAC efficiency, orientation, WWR, natural ventilation) in the middle; and the secondary thermal management cluster (roof insulation, thermal mass, SHGC, compactness, thermal bridging) at the base — provides a structured prioritisation sequence applicable to both new-build design and the energy retrofitting of existing high-rise buildings.

Fifth, the elimination of renewable energy integration, BEMS, and floor-plate daylighting design from the validated model does not imply that these considerations are unimportant in the design of energy-efficient tall buildings; rather, it confirms that they operate at a different conceptual level from climate adaptability indicators and should be treated as second-order optimisation variables applied after the primary envelope and systems performance targets have been defined.

The theoretical contribution of this study lies in the operationalisation of the climate adaptability concept for the specific typological and climatic context of high-rise buildings in cold semi-arid Iranian cities, filling a documented gap in both the building energy research literature and Iranian regulatory guidance for tall buildings. The methodological contribution lies in the application of four-round FDM with statistical convergence validation to a multi-dimensional building performance indicator development problem, demonstrating the instrument's suitability for resolving complex multi-objective design guidance problems with high expert plurality. The practical contribution lies in the production of a thirteen-indicator model directly applicable to the design assessment, regulatory specification, and retrofit prioritisation of high-rise buildings in Tabriz and comparable climatic environments.

The study is subject to certain limitations. The expert panel of fifteen members, while meeting the standard threshold for statistical significance of Kendall's W, may not fully capture regional diversity of expert opinion or the perspectives of construction industry practitioners in smaller cities with less access to the specialist building energy research community. The model's validation through FDM establishes expert consensus but does not constitute empirical testing against monitored energy performance data from operational Tabriz high-rise buildings; such testing, requiring the assembly of a monitored building performance database, remains a necessary next step for full model validation. Future research should develop context-specific performance threshold values for each of the thirteen indicators — expressed as quantitative targets (e.g., minimum wall U-value, maximum WWR, minimum HVAC COP) — calibrated through dynamic building energy simulation against the Tabriz reference climate. Parametric sensitivity analyses using tools such as EnergyPlus or DesignBuilder, combined with multi-criteria weighting using FAHP or FTOPSIS, would enable the translation of the validated indicator framework into quantitative design targets and regulatory minimum standards. Longitudinal studies comparing the energy performance of buildings designed in accordance with the proposed model against the existing building stock would provide empirical evidence of the model's practical impact and guide the progressive refinement of its indicator weights.

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