

# Prioritizing Sustainable Technological Solutions for Zero-Energy Buildings in Semi-Temperate Mountainous Climates Based on Technology Transfer Criteria

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## ABSTRACT

In cold-mountainous climates, buildings face significant heating demands and complex environmental challenges that hinder the achievement of net-zero energy performance. This study presents a dual-focused framework integrating Multi-Criteria Decision-Making (MCDM) methods—Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)—with technology-transfer criteria to evaluate and prioritize thirty sustainable technological solutions across three categories: building envelope, mechanical systems, and energy management. The framework emphasizes cost-effectiveness, technical maturity, and local compatibility to ensure practical applicability. Case-study comparisons from Turkey, Canada, and Switzerland demonstrate the transferability of optimized technological solutions. Results reveal that advanced high-performance insulation, dynamic glazing, and hybrid photovoltaic-thermal systems rank highest in combined energy savings and transfer potential. The proposed decision-support model offers policymakers and practitioners a robust tool for adapting global best practices to diverse cold-mountainous regions, contributing to the accelerated adoption of net-zero energy buildings worldwide.

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## Keywords

Zero-energy buildings;  
Technology transfer;  
Sustainability;  
MCDM;  
AHP;  
TOPSIS;  
Cold climates;  
Sustainable development

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## 1. Introduction

The building sector accounts for nearly 40% of global final energy consumption and over one-third of CO<sub>2</sub> emissions, positioning it as a critical target for decarbonization policies worldwide [1-5]. The transition toward Zero Energy Buildings (ZEBs) has therefore become a central technology for achieving sustainable energy systems and meeting the Paris Agreement goals [6–7].

However, realizing ZEBs at a large scale requires careful consideration of local climatic conditions, technological maturity, and socio-economic feasibility—factors that remain underexplored in many semi-temperate mountainous regions such as northern Iran [8].

While prior research has advanced ZEB technologies in temperate and arid contexts, cold-mountainous

climates—characterized by high heating loads, elevated humidity, and variable solar availability—pose distinct challenges for technology selection and integration. Previous studies have applied multi-objective optimization models to assess hybrid renewable energy systems in industrial and community-scale settings, highlighting the potential of PV, storage, and district heating in enhancing energy efficiency [4,9-10].

Moreover, governance and institutional frameworks have been shown to influence the success of sustainable energy transitions, particularly in regions with limited infrastructure and resource constraints [11]. Despite these advancements, comprehensive decision-making frameworks that integrate both quantitative performance

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**List of Abbreviations**

<i>AHP</i>	<i>Analytic Hierarchy Process</i>
<i>LSF</i>	<i>Light Steel Framing</i>
<i>ZEBs</i>	<i>Zero Energy Buildings</i>
<i>ICF</i>	<i>Insulated Concrete Forms</i>
<i>BIPV</i>	<i>Building-Integrated Photovoltaics</i>

<i>MCDM</i>	<i>Multi- Criteria Decision- Making</i>
<i>PV</i>	<i>Photovoltaic</i>
<i>PVT</i>	<i>Photovoltaic–Thermal</i>
<i>SDG</i>	<i>Sustainable Development Goal</i>
<i>TOPSIS</i>	<i>Technique for Order Preference by Similarity to Ideal Solution</i>

metrics and expert-driven criteria remain scarce for ZEBs in emerging semi-temperate mountainous regions [8].

The Iranian semi-temperate mountainous climate—comparable to ASHRAE Zone 4A—requires technologies that account for inconsistent solar availability and elevated heating demands. Addressing these challenges involves evaluating both the technical feasibility and economic viability of renewable technologies, particularly hybrid PV systems and storage solutions [4,7-10].

Accordingly, this study develops a hybrid Multi-Criteria Decision-Making (MCDM) framework integrating the AHP for weighting technology-transfer criteria and the TOPSIS for ranking technological alternatives. This approach enables systematic assessment of ZEB technologies under local climatic, infrastructural, and socio-economic constraints. The classification of these technological solutions is illustrated in Figure 1.

Additionally, this model incorporates criteria for technology transferability, such as cost-effectiveness, scalability, and implementation readiness, to ensure practical

applicability in a variety of cold-climate settings [9-16]. Figure 2 presents the adapted technology transfer framework employed in this study.

Unlike many existing studies that primarily focus on performance simulations or isolated cost-benefit analyses, the present research proposes a hybrid decision-making framework that combines expert judgment with quantitative metrics for evaluating and ranking ZEB technological solutions in semi-temperate mountainous climates. This study is novel in three aspects:

Integration of local climatic considerations: Unlike most ZEB studies concentrated in temperate or arid climates, this research explicitly incorporates the challenges of high humidity, cold winters, and variable solar availability typical of northern Iran (ASHRAE Zone 4A).

Transferability to climatically similar advanced contexts: The framework draws on lessons from countries with comparable climates and advanced ZEB deployment, including Germany (Bavaria, Baden-Württemberg), Switzerland, Austria, the Netherlands, and the United

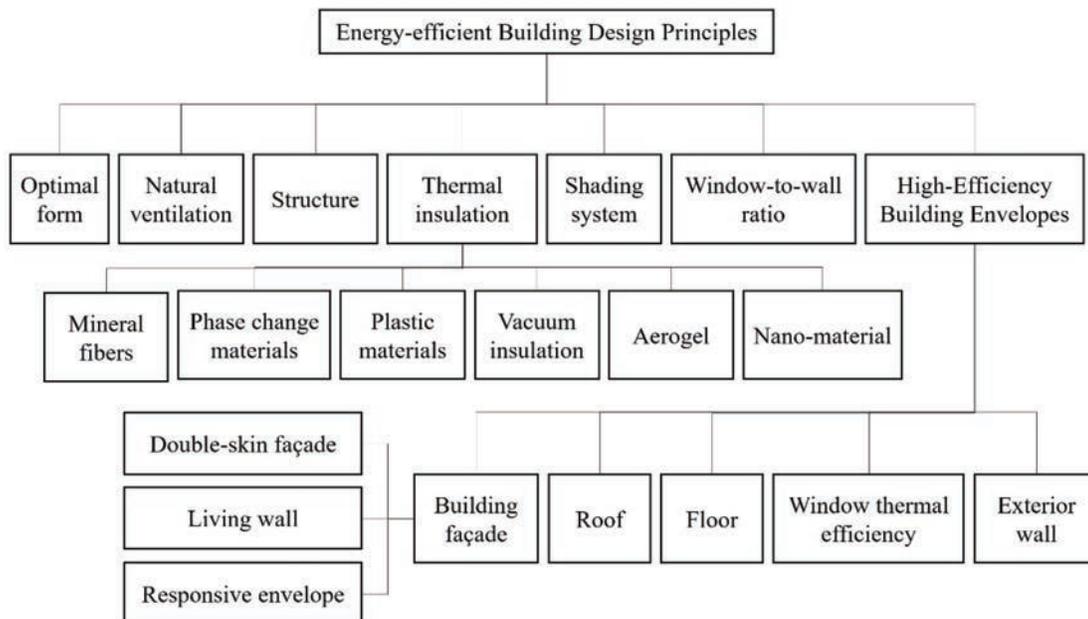


Figure 1: Classification of sustainable technological solutions for ZEBs in cold-mountainous climates.

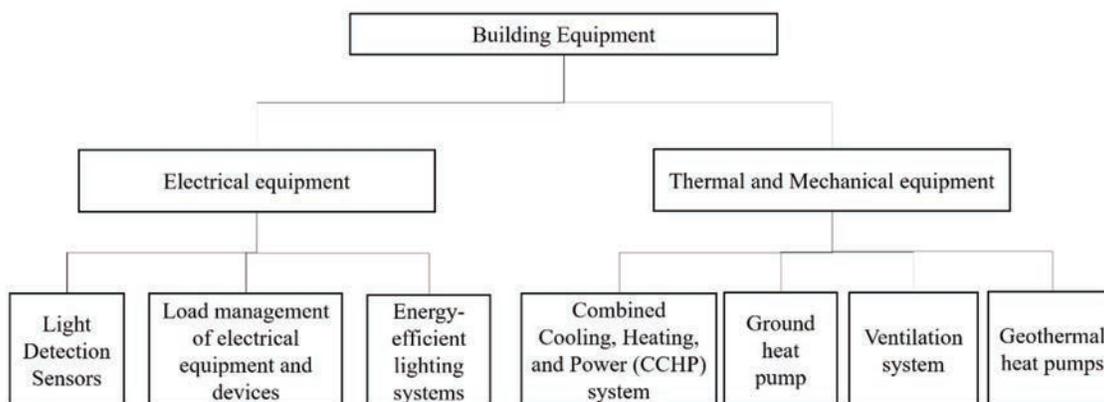


Figure 2: Technology transfer framework adapted for local implementation.

States (Northern California and Colorado). This cross-referencing allows assessment of technology transferability, scalability, and adaptation to local socio-technical constraints.

Synthesis of expert-driven and quantitative evaluation: By combining the AHP for weighting technology-transfer criteria with the TOPSIS for ranking alternatives, the methodology provides a replicable, scalable, and balanced approach for prioritizing hybrid PV systems and other ZEB technologies.

This allows decision-makers to consider both technical feasibility and economic viability under the climatic and infrastructural constraints of high-demand thermal zones. Moreover, the novelty also lies in the integration of socio-economic, environmental, and climatic criteria—rarely combined in previous ZEB prioritization studies—which provides a more holistic and context-sensitive evaluation of technological solutions.

Overall, the study advances the domain of energy systems modeling by providing a structured framework for strategic planning of ZEBs in regions with climatic complexity, geographic constraints, and emerging infrastructure, addressing a critical knowledge gap in sustainable energy transitions. The proposed framework can also be directly adopted by policymakers, offering a transparent, step-by-step structure to assess and prioritize ZEB technologies based on localized climatic and socio-economic data.

## 1.2. Technology Transfer for Zero-Energy Buildings

Technology transfer is vital for enabling developing countries to adopt advanced low-carbon solutions for ZEBs, especially in challenging semi-temperate mountainous climates [17-19]. It supports localizing proven

technologies, like passive designs and renewable-integrated envelopes from Europe and North America, where R&D is robust [20-21]. Yet, challenges such as limited funding, weak institutions, infrastructure mismatches, and diverse technology options hinder success [22-24].

This study tackles these issues by integrating technology-transfer criteria—cost-effectiveness, technical maturity, and contextual compatibility—into a multi-criteria decision-making framework. Table 1 summarizes the sub-criteria, drawn from recent literature [25-27].

## 2. Literature Review

Recent ZEB research has advanced with innovations like dynamic insulation systems, reducing heating loads by 25% in alpine areas [28], and hybrid panels, offsetting 40–60% of heating demand in cold climates [29]. A review of over fifty Scandinavian and Canadian Rockies case studies emphasizes building orientation, passive solar gain, and thermal mass for heat loss mitigation in valley terrains [30].

However, gaps remain: most studies lack adoption roadmaps, with a technology-transfer index limited to temperate climates [31], and AHP–TOPSIS applications are scarce for semi-temperate mountainous ZEBs, despite use in subtropical [32] and Mediterranean contexts [33].

In 2025, Khan and coauthors [7] highlighted integrated energy storage for resilient net-zero districts, achieving 70% self-sufficiency, while Zhang and Patel [9] identified workforce training as key to overcoming socio-economic barriers in high-altitude regions. These findings align with this study’s technology-transfer criteria (e.g., cost-effectiveness, local compatibility).

Table 1: Technology Transfer Criteria and Sub-Criteria for Zero-Energy Buildings.

Main criterion	Sub-criterion	Main criterion	Sub-criterion
Environmental feature	Greenhouse gas	Human Capabilities	Quality of life
	Water pollution		Motivation
	Human intervention		Creating educational and learning opportunities for residents
	Water consumption		Active participation
	Air pollution		Constructive attitude toward new technology
	Soil pollution		Access to better facilities and equipment
Location	Distance from a fault line	Industrial Features	Market scale
	Land slope		Product life cycle
	Access to water		Sanctions
	Topography		
Economic	Capital investment, payback period	Technical Features	Hardware characteristics
	Living standards and income of residents		Ease of hardware repair
	Job creation		Improved energy consumption of technology
	Government financial support		Ease of spare parts supply for hardware
	Technology maintenance costs		Project installation capacity
	Degree of ground interference		Compatibility with the building structure
	Guaranteed purchase price (FIT)		Compatibility with the urban landscape
	Installation cost		Compatibility with the building form
R&D Capabilities	Industry modernization	Technology Characteristics	Complexity
	Technology localization		Effectiveness
	Compatibility with national development goals		Capability
	Accessibility		Safety
	Public acceptance		Secure construction
	Compatibility and flexibility with new needs		Having specific knowledge to protect the technology
			The level of capability of the receiver in protecting technology.
Macro and Micro Policies	Government strategy		
	Having a knowledge transfer contract		

This study bridges these gaps by combining AHP–TOPSIS with a technology-transfer focus, prioritizing technically optimal, economically viable, and culturally suitable solutions for cold-mountainous ZEBs, extending applicability to community-scale planning.

### 3. Research Methods and Materials

This study employs a hybrid MCDM approach specifically tailored to the challenges of semi-temperate mountainous climates, characteristic of ASHRAE 4A zones, which exhibit cold winters, elevated humidity, and variable solar availability. The methodology integrates the

AHP for deriving criterion weights with the TOPSIS for ranking technological alternatives.

The framework was developed to systematically evaluate thirty candidate ZEB technological solutions spanning three technical domains: building envelope improvements (e.g., advanced insulation materials and high-performance glazing), mechanical systems (e.g., hybrid photovoltaic-thermal collectors, heat pumps), and energy management technologies (e.g., intelligent controls, energy monitoring systems).

These domains and corresponding technological solutions were identified through a comprehensive literature review, supported by practical applicability considerations

in Iranian semi-temperate mountainous regions [34-38, 7-8, 10]. The methodology, as shown in Figure 3, consists of three sequential and interdependent stages.

In the first stage, a systematic literature review was conducted to identify the most relevant and technologically feasible solutions for ZEBs, emphasizing approaches that have demonstrated effectiveness in climates analogous to northern Iran, including parts of Southern Europe and the European Alps [10-11]. This stage ensured that candidate technologies were grounded in both technical feasibility and prior empirical validation.

The second stage due to the large number of criteria and sub-criteria associated with technology transfer in ZEBs, a systematic prioritization was necessary. In this study, the AHP was employed to quantitatively determine the relative importance of each criterion and sub-criterion. The expert panel represented a diverse group of professionals with backgrounds in architecture, construction, and renewable energy systems.

Among the 10 respondents, 61% were male and 39% female, aged between 25 and over 40 years, ensuring both generational and experiential diversity. Most participants held advanced academic degrees (78% Ph.D. and 22% M.Sc.) and were affiliated with universities and construction companies in Sari City, northern Iran. This diversity strengthened the reliability and contextual relevance of the expert evaluations used in the AHP-TOPSIS process.

Within this framework, nine main criteria and fifty-one sub-criteria were identified, encompassing technical performance, economic feasibility, and local adaptability. A structured pairwise-comparison questionnaire was developed, comprising 174 comparisons among criteria and sub-criteria to accurately capture their relative significance. The questionnaire was distributed virtually to the expert panel, and responses were systematically collected. All calculations, including matrix normalization, weight derivation, and consistency verification, were conducted using Expert Choice software, following standard AHP consistency checks to ensure the reliability, robustness, and reproducibility of the prioritization results [8,10].

In the third stage, the TOPSIS method was employed to rank nineteen technological solutions derived from Zero Energy Buildings and suitable for cold climates, using nine technology-transfer weighted criteria. Each alternative was quantitatively assessed based on performance indicators obtained from the literature, manufacturer specifications, and regional climatic datasets.

The decision matrix, integrating both quantitative metrics and expert-assigned qualitative scores, facilitated the identification of solutions such as hybrid PV systems, photovoltaic modules, and thermal collectors as the highest-ranking options due to their dual energy output potential and adaptability to variable solar conditions. Sensitivity analyses were conducted to examine the robustness of the ranking results against variations in criterion weights and expert judgments, ensuring the reliability and stability of the proposed prioritization.

The decision matrix (Table 2) was completed by ten experts with specialized knowledge in building, energy, and architectural design, using a rating scale from 1 (least favorable) to 5 (most favorable). The expert panel was recruited, and questionnaires were distributed through a variety of digital communication channels, including professional networking and instant messaging services, to maximize reach and participation. The hybrid decision-making framework used for this analysis is illustrated in Figure 4.

### **3.1 Scope and Limitations**

This study focuses on prioritizing technological solutions for ZEBs in semi-temperate mountainous climates, specifically ASHRAE 4A zones, with a case study in Kiasar, a city administratively part of Sari County, Mazandaran Province, northern Iran, representing a semi-temperate mountainous climate distinct from Sari City.

The analysis targets thirty technological solutions across envelope design, mechanical systems, and energy management, evaluated through a hybrid AHP-TOPSIS model based on technology transfer criteria. A sample of 50 experts from academia and industry in Iran provided insights via questionnaires and interviews.

Limitations include the regional focus on Iran, which may limit generalizability to other cold-mountainous climates with different socio-economic or infrastructural contexts. The sample size of 50 experts, while sufficient for initial prioritization, could be expanded for broader representation. Additionally, the study relies on short-term performance data and expert judgments, lacking long-term empirical data on ZEB performance, an area for future research.

### **3.2 Participants**

The study engaged a diverse panel of 10 experts, randomly selected from universities across Iran and construction companies in Sari City, northern Iran—a

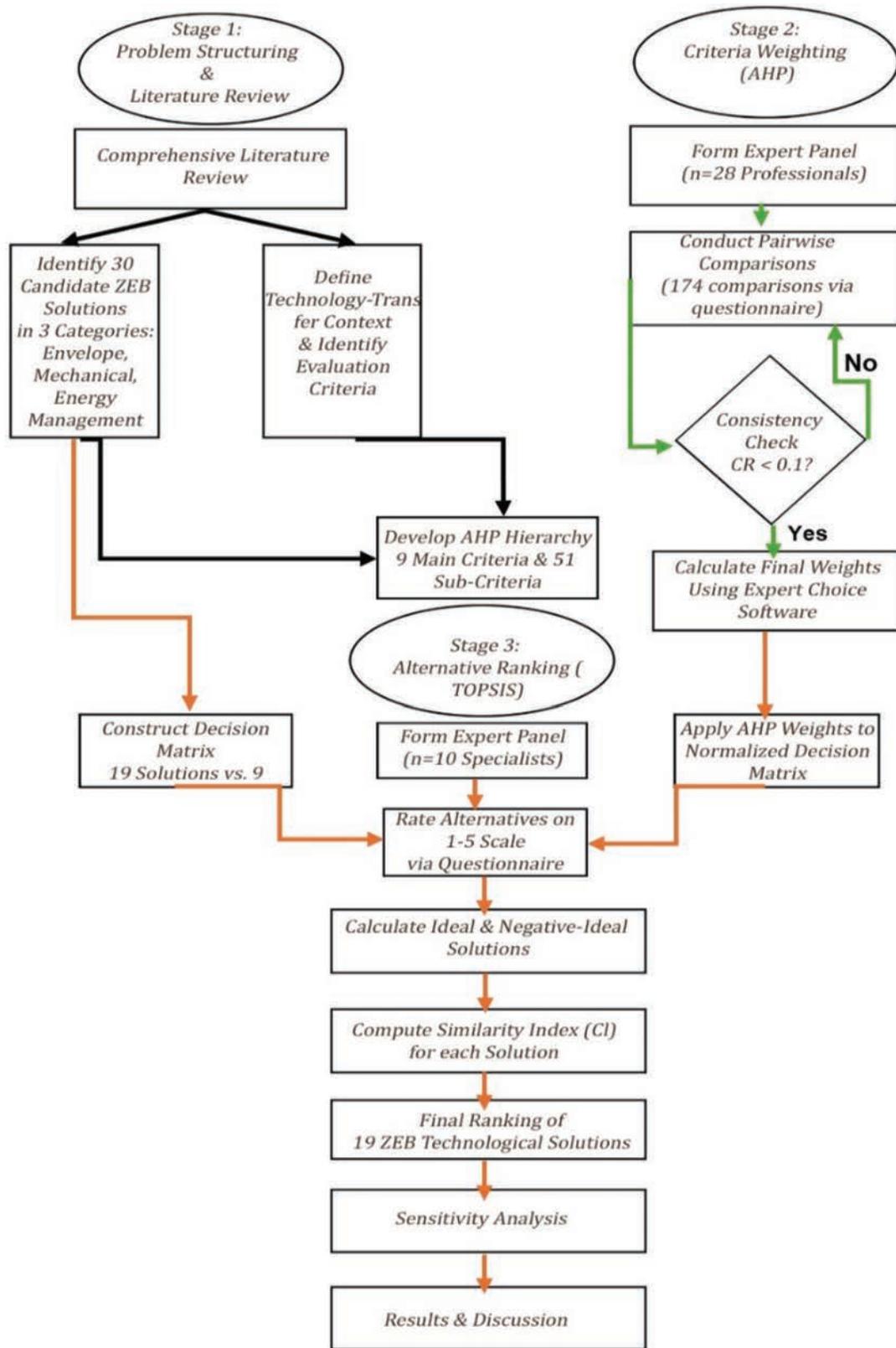


Figure 3: AHP-TOPSIS Methodology Flowchart.

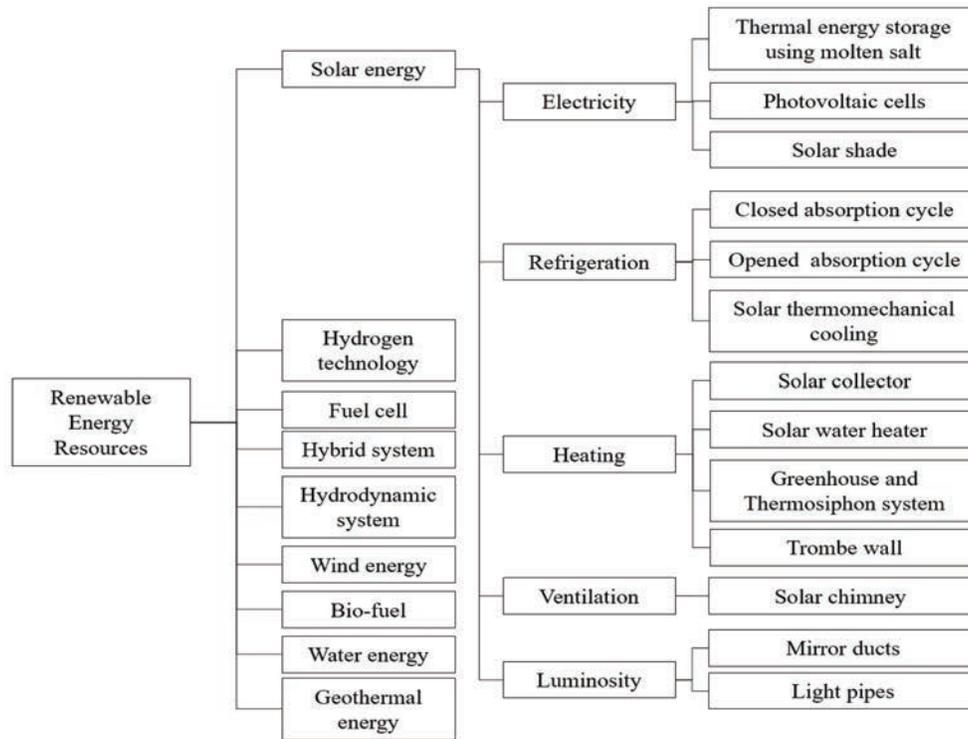


Figure 4: Zero-energy building solutions in renewable energy production.

region characterized by semi-temperate mountainous conditions. These experts possess specialized knowledge in construction, architecture, renewable energy technologies, and energy efficiency, ensuring a multidisciplinary perspective.

To enhance representativeness and address potential biases, the selection process included stakeholders from both academic and industry backgrounds, reflecting the socio-economic contexts of developing nations [39]. Ethical considerations, such as informed consent and data confidentiality, were adhered to during data collection via email and social media platforms.

### 3.3 Analytical Hierarchy Process (AHP)

The AHP methodology, widely recognized for its efficacy in multi-criteria decision-making, was employed to prioritize ZEB technological solutions by weighting criteria and sub-criteria extracted from an extensive literature review. This study identified nine primary criteria—environmental impact, industrial feasibility, technical performance, economic viability, site location suitability, human capabilities, research and development potential, micro and macro policy alignment, and technology characteristics—along with 51 sub-criteria.

These were presented to the expert panel through closed-ended questionnaires distributed via email and social media, ensuring broad participation. Pairwise comparison matrices were used to determine the relative importance of criteria and sub-criteria, with weights calculated to reflect their relevance to semi-temperate mountainous climates. This process integrates technology-transfer considerations (e.g., cost-effectiveness, technical maturity, local compatibility), distinguishing the study by aligning technical optimization with global applicability.

The hierarchical structure of the AHP model, including all criteria and sub-criteria, is illustrated in Figure 5, providing a visual framework for selecting the most suitable ZEB design technological solutions.

### 3.4 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method was applied to rank the prioritized technologies based on the weighted criteria from AHP, incorporating technology-transfer factors. Experts evaluated 19 technologies using a 1–5 scale (1 = best, 5 = worst) in a decision matrix, which was normalized and weighted to compute similarity indices.

Table 2: Decision Matrix for TOPSIS.

	Site Selection	Human Capability	Environmental	Research and Development Capability	Industrial Features	Micro and Macro Policies	Technological Characteristics	Technical Feasibility	Economic
Heavy Wall	4.3	2.9	3.5	2.7	2.7	2.5	1.7	1.7	3.6
Pond Roof	3.6	2.9	3.5	1.7	2.1	1.9	2.1	3.1	2.4
Climate-Adaptive Building Envelope	2.6	3.3	4	3.2	3.2	2.8	3.7	4.1	2.8
Innovative Thermal Insulation	3.1	3.9	3.7	3.3	3.1	2.7	3.2	4.5	3.6
Advanced Structural Technologies	3.6	3.3	2.9	3.3	3.2	3	3.9	4.5	3.5
Wind Cowl	2.3	2.6	3.1	2.6	3	1.7	2.9	2.7	3.1
Heat Recovery System	3.2	3.7	3.2	3.3	4	3.4	3.2	3.8	4.4
Ground-Source Heat Pumps	2.8	3.2	4.1	3.8	4	2.6	2.9	3.5	3.9
Geothermal Heat Pumps	3.7	3.7	4	4.3	3.5	3.2	3	3.6	3.3
Smart Building Systems	2	3.6	3.2	4.2	3	2.3	4.1	4	2.8
Solar Water Heater	4.9	4.1	4.2	3.4	3.8	3.4	2.9	3.3	4.1
Trombe Wall	3.6	3.4	3.4	3.1	4.2	3.8	3.1	3.4	3.8
Greenhouse and Thermosiphon System	3.6	3.1	3.1	3.4	3.9	3.1	3.4	3.5	4.3
Solar Collector	3.3	3.5	3.3	3.8	4.1	4.2	3.8	3.5	3.6
Photovoltaic System	3.1	3.6	4.2	4.8	3.7	3.6	3.9	3.9	3.5
Water Circulation System	3.2	3.1	4.1	4.1	3.4	3.2	3.2	4.3	3.2
Small Wind Turbine	3.9	3.4	3.3	3.2	4.1	2.7	3.5	4	3.5
Hybrid Systems	2.9	4.2	3.9	3.8	4.4	3.2	4.7	4.2	4
Biofuels	3.2	2.9	4.9	3	2.8	2.9	3.1	2.7	2.5

This step ensured that the selected technologies are not only technically sound but also feasible for transfer across diverse regions, supporting sustainable development goals. For instance, PV systems were rated highly on technical maturity (score: 4.5) and cost-effectiveness (score: 4.0), reflecting their suitability for semi-temperate mountainous climates.

#### 4. Results

The results section presents a comprehensive analysis of the prioritized technological solutions for ZEBs in semi-temperate mountainous climates. Using the TOPSIS-based evaluation framework, nineteen climate-appropriate ZEB measures were assessed across

nine weighted technology-transfer criteria. Findings are detailed in terms of technical performance, economic viability, and local adaptability, providing an evidence-based ranking that highlights the most promising technologies for optimizing energy efficiency under cold, humid, and variable solar conditions.

##### 4.1 AHP Results

Following the completion of pairwise comparison matrices, inconsistency rates for all matrices were calculated to be below 0.10, a threshold that confirms the stability and compatibility of the expert evaluations, ensuring robust decision-making in this multi-criteria analysis [39-41]. The pairwise comparisons were aggregated using the

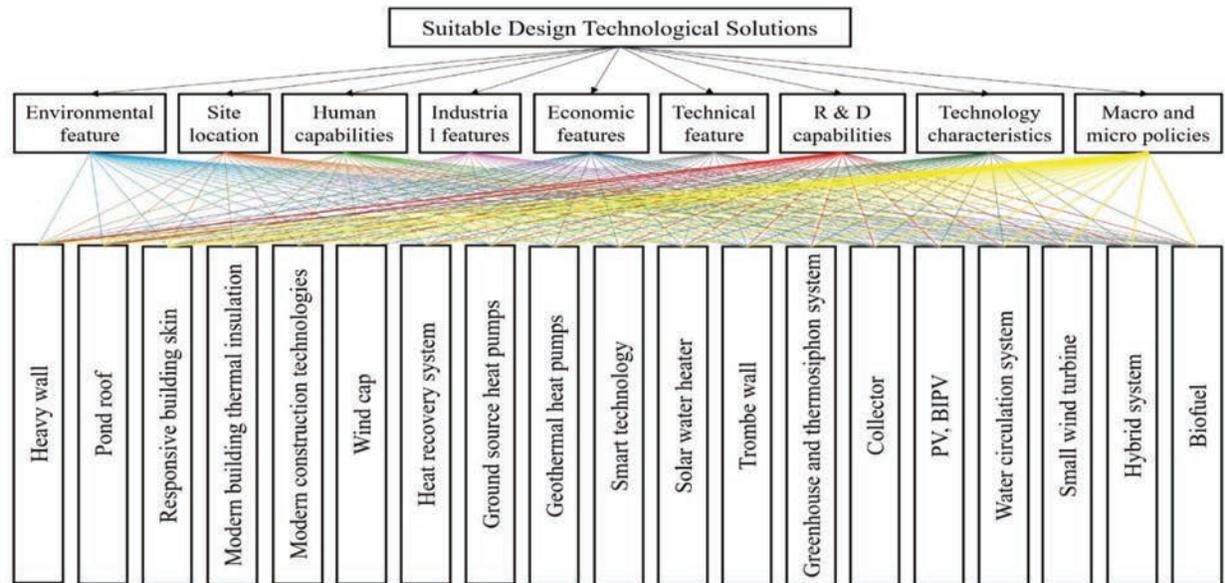


Figure 5: Hierarchical structure of the AHP model for ZEB technological solution prioritization in semi-temperate mountainous climates.

geometric mean, with equal weight assigned to each participant’s responses to reflect a balanced consensus.

The resulting weights for the nine main criteria—environmental impact, industrial feasibility, technical features, economic viability, site location suitability, human capabilities, research and development potential, policy alignment, and technology characteristics—are presented in Table 3. The analysis identified economic viability (weight: 0.129), technical features (weight: 0.120), and technological aspects (weight: 0.116) as the three most critical criteria, highlighting their importance in prioritizing ZEB technological solutions for cold mountainous climates.

These findings underscore the need for cost-effective and technically mature solutions, key factors in facilitating technology transfer to developing regions and supporting Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy) [36].

#### 4.2 TOPSIS Results

The TOPSIS methodology began with the construction of an initial decision matrix, a critical step in multi-criteria decision-making that facilitates the evaluation of ZEB technological solutions [4]. In this study, the matrix comprised 19 rows representing diverse research technological solutions for ZEB technologies and 9 columns corresponding to the criteria identified through the AHP process (e.g., economic viability, technical features).

This matrix was completed by the 10 expert respondents—specialists in sustainability and energy from Iran—using a 1–5 scale, where 1 denoted the most favorable technological solution and 5 the least favorable, ensuring a robust assessment tailored to semi-temperate mountainous climates. Subsequent steps involved normalizing the decision matrix to account for varying scales and weighting it based on the AHP-derived criteria to reflect their relative importance. The similarity index, a key metric in TOPSIS, was then computed for each technological solution, with higher values indicating superior ranking based on proximity to the ideal solution.

The results, detailed in Table 4, revealed that hybrid photovoltaic systems ranked first, building-integrated photovoltaics second, and solar collectors third, reflecting their combined excellence in energy savings, technical maturity, and transfer potential. These rankings align with case-study validations from Turkey, Canada, and Switzerland, where hybrid PV systems have demonstrated adaptability to cold mountainous conditions, reducing heating demands by up to 60% [18].

This prioritization supports the global applicability of the framework, particularly for developing regions seeking cost-effective and locally compatible ZEB solutions, thereby contributing to SDG 7 (Affordable and Clean Energy) and enhancing climate resilience [36]. The

Table 3: Weights and Rankings of AHP Criteria for ZEB Technological Solution Prioritization.

Criteria	Criteria weight	Sub-criteria	Sub-criteria relative weight	Sub-criteria final weight	Rank
Environmental Feature	0.106	Greenhouse gases	0.163	0.0173	23
		Water pollution	0.176	0.0187	18
		Human intervention	0.165	0.0175	21
		Water consumption	0.155	0.0164	28
		Air pollution	0.187	0.0198	12
		Soil pollution	0.154	0.0163	30
Industrial Features	0.111	Market scale	0.328	0.0364	4
		Product life cycle	0.286	0.0317	5
		Sanctions	0.387	0.0430	2
Economic Features	0.129	Capital investment and payback period	0.134	0.0173	22
		Living standard	0.136	0.0175	20
		Job creation	0.147	0.0190	15
		Government financial support	0.133	0.0172	24
		Maintenance cost	0.118	0.0152	36
		The amount of interference on the ground	0.098	0.0126	49
		Feed-In Tariff (FIT)	0.108	0.0139	45
		Setup cost	0.127	0.0164	29
Technology Characteristics	0.116	Complexity	0.094	0.0109	51
		Influence	0.145	0.0168	26
		Ability	0.145	0.0168	26
		Safety	0.172	0.0200	10
		Safe construction	0.172	0.0200	10
		Speed	0.135	0.0157	34
		The degree of capability and ability of the receiver to protect the technology	0.137	0.0159	33
Human Capabilities	0.101	Updating the construction industry	0.142	0.0143	43
		Technology development	0.128	0.0129	48
		Localization of technology	0.145	0.0146	41
		Compatibility with the country's development goals	0.147	0.0148	39
		Availability	0.138	0.0139	44
		General admission	0.123	0.0124	50
		Adaptability and flexibility to new needs and opportunities	0.177	0.0179	19
Site Location	0.094	Distance from the fault	0.031	0.0291	6
		Land slope	0.227	0.0213	7
		Access to water	0.26	0.0244	8
		Elevation	0.203	0.0191	14

Contd...

Table 3: *Contd...*

Technical Features	0.0120	Hardware feature	0.108	0.0130	47
		Ease of hardware repairs	0.12	0.0144	42
		Improving technology energy consumption	0.13	0.0156	35
		Easy supply of hardware spare parts	0.135	0.0162	31
		Project installation capacity	0.123	0.0148	40
		Compliance with the building structure	0.126	0.0151	37
		Adaptation to the urban landscape	0.125	0.0150	38
		Compliance with the building form	0.133	0.0160	32
R&D Capabilities	0.108	Quality of life	0.123	0.0133	46
		Motivation	0.158	0.0171	25
		Creating educational and learning opportunities for people in the region	0.175	0.0189	16
		Active participation	0.187	0.0202	9
		Constructive attitude to new technology	0.181	0.0195	13
		Access to better facilities and equipment	0.175	0.0189	16
Micro and Macro Policies		Government strategy	0.632	0.0720	1
		Having a non-codified knowledge transfer contract	0.368	0.0420	3

emphasis on renewable technologies also underscores environmental benefits, such as reduced carbon emissions, which are critical for sustainable development in mountainous ecosystems [42].

The analysis also provided insights into specific technological solution categories. In building design, modern construction technologies (e.g., light steel framing [LSF], insulated concrete forms [ICF], prestressed concrete) ranked highest, followed by advanced insulation (e.g., aerogel, nanomaterials), due to their adaptability to cold climates. These technologies excel in minimizing heat loss and maintaining structural integrity under extreme weather conditions.

The moderate ranking of advanced insulation materials, as shown in Figure 6 and Table 4, reflects their significant but not dominant role due to high initial costs despite strong cost-effectiveness over time, as supported by Zhang and coauthors in [9]. This outcome is consistent with the AHP weighting results, where economic

criteria such as initial investment exerted greater influence than long-term performance benefits.

Other notable considerations included responsive building skin, heavy walls, wind caps, and pond roofs. Turning to the mechanical installations, the first rank went to geothermal heat pumps, followed by heat recovery systems and ground heat pumps. Moreover, in the field of solar heating technological solutions, solar collectors were ranked first, followed by solar collectors, solar water heaters, Trombe systems, greenhouses, and thermosiphon systems, which were ranked second to fifth, respectively. Regarding renewable energy technological solutions, hybrid systems were ranked first. The subsequent ranks were occupied by photovoltaic systems, wind turbines, and biofuels (Figure 6).

### 4.3 Discussion

The prominence of hybrid photovoltaic-thermal systems as the top-ranked technological solution in the

Table 4: TOPSIS Rankings and Similarity Indices of ZEB Technological solutions.

Technological solutions	Distance to the positive ideal	Distance to the Negative ideal	Final score	Rank
Heavy wall	0.042	0.023	0.3507	17
Pond roof	0.047	0.016	0.2559	19
Responsive building skin	0.031	0.030	0.4910	14
Modern building thermal insulation	0.029	0.031	0.5155	12
Modern construction technologies	0.027	0.035	0.5617	9
Wind cap	0.045	0.016	0.2630	18
Heat recovery system	0.02	0.035	0.5697	7
Ground source heat pumps	0.030	0.030	0.4982	13
Geothermal heat pumps	0.024	0.034	0.5863	5
Smart technology	0.035	0.032	0.4783	15
Solar Water Heater	0.022	0.040	0.6411	4
Trombe Wall	0.026	0.035	0.5769	6
Greenhouse and thermosiphon system	0.027	0.034	0.5591	11
Collector	0.022	0.040	0.6430	3
PV, BIPV	0.020	0.041	0.6727	2
Water circulation system	0.026	0.034	0.5653	8
Small wind turbine	0.026	0.034	0.5614	10
Hybrid systems	0.021	0.044	0.6792	1
Biofuel	0.034	0.027	0.4379	16

TOPSIS analysis underscores a significant shift toward integrated renewable energy solutions, particularly suited to the heating-dominated conditions of semi-temperate mountainous climates. This finding contrasts with previous studies in temperate regions, where standalone photovoltaic systems often suffice due to milder winters and balanced energy demands [43].

The hybrid PV systems’ ability to simultaneously generate electricity and thermal energy—reducing heating demands by up to 60% as noted by Lee and coauthors in and coauthors in [18]—highlights their adaptability to the cold, humid conditions characteristic of ASHRAE 4A climate zones, such as parts of the U.S. Northeast or northern Europe. This dual-output capability addresses a critical gap identified in the literature, where traditional PV systems struggle to meet the elevated thermal loads of high-elevation environments with inconsistent solar availability [30].

The high ranking of advanced insulation materials (e.g., aerogel, nanomaterials) and modern construction technologies (e.g., LSF, ICF) further emphasizes the importance of envelope efficiency in mitigating heat

loss, a priority in cold mountainous settings. These findings align with Papadopoulos and coauthors in and coauthors in [3], who noted the efficacy of topographical adaptations in ZEB design, yet extend the discussion by integrating technology-transfer criteria such as cost-effectiveness and local compatibility.

The adaptability of LSF and ICF to extreme weather conditions, as validated by case studies in Turkey, Canada, and Switzerland, suggests a scalable solution that could be replicated in developing regions with similar climates, such as the Himalayas or Andes, pending further validation.

However, the reliance on a regionally specific expert panel from Sari City, Iran, introduces potential bias, as their evaluations may reflect local construction practices and resource availability rather than a globally representative perspective. This limitation is compounded by the absence of long-term performance data, which is crucial for assessing the durability and economic viability of these technological solutions over decades—a concern raised in recent reviews of ZEB technologies. Additionally, the exclusion of cooling-oriented technological solutions, while justified by the heating focus of

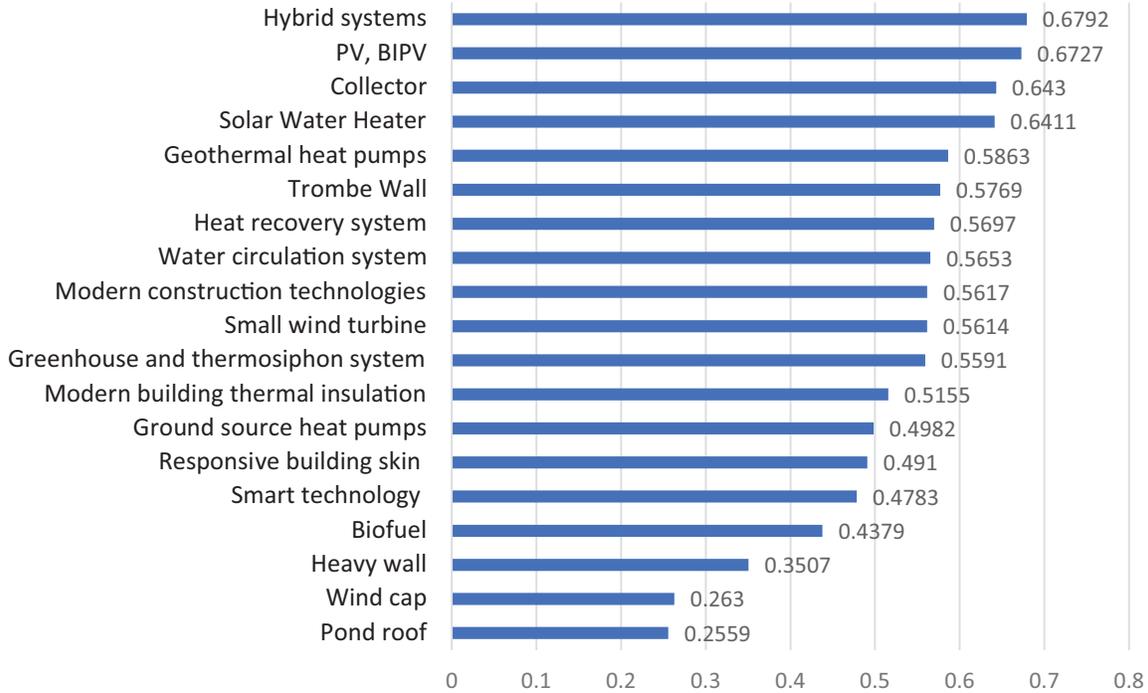


Figure 6: Final ranking of zero-energy building technological solutions.

the study, may overlook hybrid systems’ potential in transitional seasons, an area warranting future investigation.

The integration of AHP and TOPSIS with technology-transfer criteria represents a methodological advancement over isolated simulation-based approaches [31], offering a replicable framework for policymakers. Yet, the study’s emphasis on building-level interventions could be expanded to explore district-scale energy planning, aligning with IJSEPM’s interest in broader sustainable energy systems. The environmental benefits, such as reduced carbon emissions from prioritizing renewable technologies, also support SDG 13 (Climate Action).

However, socio-economic impacts—such as job creation from the local manufacturing of insulation materials—require further quantification to address SDG 7 (Affordable and Clean Energy) fully. To further contextualize these findings, a comparative analysis with existing studies reveals both convergences and divergences. For instance, Li and Kumar in [12] applied AHP–TOPSIS to rank passive design measures in subtropical climates, prioritizing shading and ventilation, which aligns with the emphasis on natural ventilation and shading in this study’s cold mountainous context.

However, their focus on cooling efficiency contrasts with the heating-centric priorities here, reflecting the influence of climatic variability. Similarly, Ascione and coauthors in [13] evaluated energy retrofit of educational buildings towards nearly zero-energy performance, where hybrid PV systems ranked lower due to abundant solar resources reducing the need for thermal output, unlike the ASHRAE 4A zones, where dual energy generation is critical. This suggests that the adaptability of hybrid PV systems is climate-specific, a nuance underexplored in temperate-focused studies like Zhang and coauthors in and coauthors in [43].

Moreover, these comparisons highlight the need for region-specific validation, potentially through cross-climatic pilot projects, to refine the framework’s global applicability. In contrast, the high ranking of advanced insulation materials in this study resonates with findings from Garcia and coauthors in and coauthors in [44], who highlighted thermal mass as a key factor in mountainous ZEBs. Yet, their simulation-based approach lacked the technology-transfer lens applied here, which prioritizes cost-effectiveness and local compatibility—criteria that proved decisive in the TOPSIS rankings.

This comparison underscores the value of integrating expert judgment with quantitative metrics, as opposed to isolated modeling, to address real-world implementation barriers. However, studies in Nordic climates (e.g., Gibbons and Javedin [37]) suggest that geothermal heat pumps, which ranked highly in mechanical systems here, may require significant upfront investment, a factor mitigated in this study by the emphasis on scalable, cost-effective solutions. These differences highlight the need for region-specific adaptations, a gap this framework begins to address.

The environmental and socio-economic implications also warrant comparison. While Christopher and coauthors in and coauthors in [31] noted reduced carbon emissions from renewables, they did not quantify job creation potential, an area this study suggests for future exploration through local manufacturing of insulation. This comparative lens reinforces the study's contribution but also indicates areas where further validation—such as cross-climatic field trials—could strengthen its global applicability.

Additionally, the emphasis on advanced insulation materials aligns with findings from Cabeza and Chàfer in [29], who reported a 20-30% reduction in energy demand through high-performance envelopes in alpine settings. This synergy highlights the potential of envelope optimization to complement renewable systems like hybrid PV, yet their study lacked a technology-transfer perspective, which this research addresses through criteria like local compatibility. This integration not only enhances energy efficiency but also supports SDG 13 by mitigating carbon emissions, a critical factor in cold mountainous ecosystems where heating dominates energy use.

In conclusion, this study provides a robust foundation for ZEB deployment in cold mountainous climates, with hybrid PV systems and advanced envelope solutions leading the way. Future research should focus on multi-year field trials in ASHRAE 4A and similar zones, incorporate diverse expert inputs to mitigate regional bias, and assess the feasibility of scaling these technological solutions to net-zero energy communities. Such efforts will enhance the framework's global applicability and contribute to the journal's mission of advancing sustainable energy planning.

## 5. Conclusions

The conclusions synthesize the key insights derived from the multi-criteria evaluation of ZEB technologies. Emphasis is placed on the applicability of hybrid PV

systems, high-performance building envelopes, and energy management solutions in semi-temperate mountainous regions. This section discusses the implications for sustainable building design, identifies potential implementation barriers, and outlines recommendations for policymakers, practitioners, and researchers aiming to advance energy-efficient construction in climates with complex thermal and solar dynamics.

## 5.1 Summary of Findings

This study aimed to develop and prioritize operational and executive technological solutions for ZEBs in semi-temperate mountainous climates, contributing to sustainable development and climate resilience. Leveraging expert input, the research evaluated a range of ZEB technological solutions using a novel decision-support framework that integrates the AHP and TOPSIS with technology-transfer criteria. Nine main criteria, 51 sub-criteria, and 19 technological solutions, derived from a comprehensive literature review, were analyzed within the AHP model to assess their suitability for cold mountainous settings.

The AHP results identified economic viability and technical features as the most influential criteria, underscoring their critical role in selecting ZEB technological solutions for resource-constrained environments. Subsequent TOPSIS analysis, informed by these weights and focusing exclusively on heating demands by excluding cooling-oriented technological solutions, ranked hybrid photovoltaic systems as the top priority, followed by building-integrated photovoltaics and solar collectors.

This prioritization reflects the hybrid system's ability to enhance energy efficiency by integrating PV with other renewable sources, reducing heating demands by up to 60% in cold climates [18]. Essential design technological solutions, including optimal building orientation, compatibility with topography and climate, natural ventilation, appropriate opening types and ratios, and shading, were also deemed vital for ZEB success in these regions.

These findings highlight a sustainable solution that minimizes environmental impact while addressing the socio-economic realities of developing mountainous areas, such as Turkey, Canada, and Switzerland, where case studies validate the transferability of these technological solutions [5].

The prioritized technological solutions, including hybrid PV systems and advanced insulation, are particularly suitable for the 4A climate zone as defined by ASHRAE, characterized by cold winters and humid conditions, due to their effectiveness in managing

heating loads and leveraging solar gain in such environments. By aligning with SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action), this framework supports global knowledge exchange and equitable access to clean energy technologies [33].

### **5.2 Scalability and Applications**

Beyond individual buildings, the scalability of these technological solutions to net-zero energy communities offers a promising avenue for future energy planning. Integrated systems like hybrid PV, when combined with community-scale energy storage, could enhance resilience and reduce transmission losses, as suggested by research on smart energy systems [45]. This expansion could address the socio-economic needs of larger populations, fostering local job creation through the deployment of advanced construction technologies.

Although solar availability fluctuates in mountainous regions, hybrid photovoltaic-thermal systems mitigate this limitation by simultaneously harnessing thermal and electrical energy, maintaining efficiency even under variable solar conditions. Beyond individual buildings, the scalability of these technological solutions to net-zero energy communities offers a promising avenue for future energy planning.

Integrated systems like hybrid photovoltaic-thermal systems, when combined with community-scale energy storage, could enhance resilience and reduce transmission losses, as suggested by emerging research in 2025 [40]. Osorio-Aravena and coauthors in [8] demonstrate the role of solar PV and storage in achieving 100% renewable energy systems in challenging terrains like Chile, aligning with our TOPSIS findings, prioritizing hybrid PV systems in cold-mountainous climates.

Similarly, Viesi and coauthors in [10] show multi-objective optimization for full decarbonization in Alpine energy communities, emphasizing sector coupling and RES integration. By adopting such models, ZEB technological solutions can foster local job creation and support SDG 7 (Affordable and Clean Energy) through shared renewable infrastructure. By following the proposed AHP-TOPSIS framework, policymakers can systematically assess technology alternatives using localized criteria weights, thereby transforming expert-based evaluations into evidence-driven policy actions.

### **5.3 Policy Implications**

Governments should prioritize incentives for hybrid renewable systems, such as hybrid photovoltaic-thermal

systems, which ranked highest in our TOPSIS analysis (Table 3) due to their ability to reduce heating demands by up to 60% in cold-mountainous climates [15]. Gohari and Larssæther [11] emphasize co-creative governance in ZEB projects like Zero Village Bergen, highlighting the need for addressing power relations and stakeholder conflicts in sustainable transitions.

Drawing on these insights, policymakers in regions like Iran should implement subsidies for local manufacturing of advanced insulation materials and hybrid PV systems, potentially reducing costs through innovation support policies as demonstrated in solar energy cost reduction studies [46]. Additionally, training programs for local contractors can enhance technical maturity, aligning with SDG 7 (Affordable and Clean Energy) and fostering inclusive economic growth.

### **5.4 Future Research Directions**

Future research should delve deeper into the long-term performance metrics of the top-ranked technological solutions identified in this study, such as hybrid photovoltaic-thermal systems and advanced insulation materials, which demonstrated high adaptability to semi-temperate mountainous climates (mean scores of 4.3 and 4.5, respectively, in Table 5).

Longitudinal studies are needed to assess their energy efficiency, durability, and maintenance costs over a decade, particularly in ASHRAE 4A zones like those in Iran, where inconsistent solar availability and extreme heating loads pose unique challenges. These studies could employ real-time monitoring systems and life cycle assessment methodologies to quantify performance degradation and environmental impacts, addressing a key limitation of the current dataset, which lacks long-term data.

Additionally, the socio-economic impacts of scaling these technological solutions should be investigated, focusing on job creation, training requirements for local workforces, and affordability for diverse socio-economic groups. For instance, the high initial costs of advanced insulation (noted in Section 4.2) suggest a need for economic modeling to evaluate subsidies or financing models that could enhance adoption rates. This aligns with the findings of Osorio-Aravena and coauthors in [8], who emphasized the role of integrated energy storage and policy support in sustainable transitions across diverse regions.

Furthermore, community-scale implementations offer a promising avenue, particularly by integrating these

solutions with smart grid technologies to optimize energy distribution in cold-mountainous regions. Research could explore pilot projects that combine hybrid PV systems with microgrids, assessing their resilience to topographical variations and energy demand fluctuations.

Such studies should incorporate stakeholder engagement (e.g., local governments and energy providers) to identify barriers and facilitators, as suggested by Gohari and Larssæther in [49], who highlighted the importance of co-creative governance in energy planning. Data collection for these projects could involve advanced simulation tools (e.g., Energy Plus) and multi-criteria optimization models to refine the AHP-TOPSIS framework for larger scales.

Finally, validating the transferability of this framework to other cold climates (e.g., ASHRAE 6A or 7A zones) requires comparative case studies, potentially leveraging international collaborations to adapt criteria like site selection and human capability. These efforts would enhance the decision-support tool's global applicability, providing policymakers with actionable insights to accelerate ZEB adoption worldwide.

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No potential conflict of interest was reported by the author(s).

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