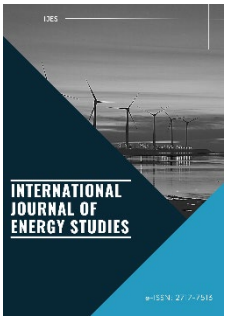
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Net zero energy residential architecture in hot-humid climate regions: Design principles and feasibility analysis

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Highlights

- A climate-specific NZEB design guideline was developed for Turkey's hot-humid regions.
- Passive, active and renewable energy systems were integrated within a systematic design framework.
- A detached residential building in Antalya was used as the case study.
- Energy performance was analyzed through dynamic simulations using DesignBuilder software.
- Photovoltaic integration enabled the building to achieve Net zero energy building performance.

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ABSTRACT

This study presents the development of a Net Zero Energy Building (NZEB) design guide specifically tailored for new buildings to be constructed in Turkey's hot-humid climate zone, along with analyses and evaluations regarding the functioning of this guide. Within the scope of the study, a design guideline for NZEBs was created by establishing design decision steps involving passive design strategies, passive systems, active systems, and energy generation systems specific to the hot-humid climate zone. Antalya, a city located within this climatic region, was selected as the case study area. Based on the design decision steps outlined in the guide, a detached single-family residence was designed, and energy simulation analyses were conducted using the DesignBuilder software to evaluate the efficiency of the proposed systems. As a result of these evaluations, the most energy-efficient system for each parameter was selected, thereby minimizing the building's energy demand while ensuring the necessary indoor comfort conditions. In the final stage, photovoltaic panels were installed on the roof of the building to meet the remaining energy demand through solar energy, achieving compliance with the NZEB standard.

Keywords: Energy- efficient design, Net zero energy, Passive design criteria, Hot- humid climate zone, Solar gain

1. INTRODUCTION

Energy efficiency and sustainability in buildings are among the most significant and prioritized issues in today's construction sector. Due to buildings accounting for approximately 40% of global energy consumption [1], the development and widespread adoption of energy-efficient design approaches emerge as a fundamental strategy in combating climate change. In this context, Net Zero Energy Buildings (NZEBs) have gained a significant position in energy-efficient design approaches, possessing the potential both to reduce the amount of energy required for ensuring the necessary comfort conditions in buildings and to obtain the requisite energy from renewable energy sources.

The design process for net zero energy buildings, rather than focusing solely on energy generation, primarily involves minimizing energy demand through passive design decisions and the utilization of passive systems, subsequently enhancing energy efficiency with active systems, and ultimately integrating renewable energy systems. Consequently, accurate analysis of climatic data and the adoption of region-specific design decisions play a decisive role in achieving the net zero energy building objective. Recent reviews on adaptive thermal comfort emphasize that comfort expectations, acceptable indoor temperature ranges, and building energy performance are strongly influenced by climatic context, occupant adaptation, and building typology [59].

Hot-humid climate regions are characterized by consistently high temperatures and relative humidity levels throughout the year, necessitating the careful management of natural ventilation and heat gain-loss balances. The primary factor increasing energy consumption in these regions is the preference for mechanical cooling systems to achieve comfort conditions [2]. Therefore, designing net zero energy buildings in hot-humid climate regions mandates a comprehensive evaluation of climate-appropriate passive design decisions and passive systems. Concurrently, the selection of active systems and the integration of renewable energy sources, such as solar and wind energy, in alignment with local potentials, are of paramount importance for optimizing the building's energy performance.

In this context, the study aims to develop a guide for net zero energy building design, taking into account the specific conditions of Turkey's hot-humid climate region. The guide proposes a multi-stage decision-making process based on passive and active design decisions and the integration of renewable energy generation systems. Energy simulations are conducted on a sample residential

building designed in accordance with the developed guide to evaluate the performance of the systems and test their applicability.

The objective of this study is to develop a practical and guiding NZEB design approach capable of achieving energy efficiency targets under the specific conditions of Turkey's hot-humid climate zone, aiming to contribute to energy policies at both academic and implementation levels.

2. THEORETICAL FRAMEWORK

NZEB Concept and Global Vision The building sector, responsible for approximately 36% to 40% of global energy consumption, has centered the "Nearly Zero Energy Building (nZEB)" concept in the fight against climate change. In the literature, nZEB is defined as buildings with minimized energy demand, where the remaining requirement is largely met by on-site or nearby renewable sources. Although international organizations such as IEA (International Energy Agency), EPBD (Energy Performance of Buildings Directive), and US DOE (United States Department of Energy) have set phased timelines to achieve this goal, nZEB definitions and calculation methodologies vary according to countries' local conditions. The fundamental principle traditionally follows a three-stage hierarchy:

- reducing energy loads through passive design decisions
- selection of high-efficiency active systems
- integration of renewable energy technologies.

Hot and humid climate regions are considered the most challenging geographies for nZEB targets due to year-round high temperatures, intense solar radiation, and the need for humidity control. Al-Saadi et al. (2023) [42], in their analysis of educational buildings in Oman, showed that passive strategies alone (insulation, high-performance glazing) were not sufficient, but that efficient active systems (VRF) and photovoltaic (PV) integration could achieve energy consumption reductions of up to 28.5%. Sarir and Sharifzadeh (2024) [43] demonstrated the technical feasibility of "Positive Energy Buildings (PEB)" models, where buildings produce more energy than they consume, through polyurethane insulation and wind turbine integration under similar climatic conditions. Focusing on the hot and humid regions of Iran, Mohammadi and Mousavi (2022) [44] identified lighting power density, airtightness, and wall insulation as the most critical parameters determining energy performance. Abuimara et al. (2025) [45], in the example of the United Arab

Emirates, emphasized the importance of the social dimension by highlighting that nZEB prototypes must be compatible with local culture and family structure.

Digital workflows and Artificial Intelligence (AI) are brought to the forefront to predict and optimize nZEB performance. Ibrahim et al. (2025) [46] highlighted the revolutionary role of Artificial Intelligence in increasing operational efficiency through predictive energy analytics and smart HVAC control. Ohene et al. (2024) [47] demonstrated the cost-effectiveness of northern orientation and natural ventilation using Life Cycle Cost (LCC) optimization in tropical climates; Kaitouni et al. (2023, 2024) [48,49] showed that Building-Integrated Photovoltaics (BIPV) systems could exceed 30% of the total energy output with the digital workflow they developed for semi-arid regions. Salem et al. (2025) [50] stated that Building Information Modeling (BIM)-based energy analyses are critical in determining the impact of location-specific factors on energy efficiency. Furthermore, Rezaee et al. (2021) [51] proposed parametric frameworks based on sensitivity analyses to guide decision-makers in the early stages of architectural design.

It has gained momentum in line with the 2053 net zero emission target and the Paris Agreement. Diker and Yazıcıoğlu (2025) [52] examined the conversion of qualified housing stock in Istanbul to nZEB and determined that photovoltaic systems are the most cost-optimal solution (14% efficiency increase). Acar and Kaska (2022) [53], investigating nZEB design pathways for Turkey's four different climate regions (Osmaniye, Istanbul, Konya, Erzurum), found that achieving net energy balance in Mediterranean and semi-arid climates is technically possible using the NSGA-II algorithm, but cold regions like Erzurum require more complex solar solutions. Takva et al. (2022) [54] discussed the PEB concept in an architectural context, emphasizing that climate-sensitive design is not only an energy-saving strategy but also one that extends the lifespan of the building stock.

Upon reviewing the existing literature, while general nZEB guides for hot and humid climates or theoretical optimization studies for Turkey as a whole exist, there is a noticeable lack of a holistic design guide developed for Turkey's unique 1st Climate Region (Antalya example) that can guide decision-makers from the initial architectural design phase to the production phase. While most studies in the literature focus either on the improvement of existing building stock (retrofit) or on specific simulation algorithms, this study fills this gap by basing its work on Turkey's most current TS825:2024 standards. The study defines a unique architectural roadmap for the hot and humid

climate zone that is sustainable, applicable, and fully compliant with regulations, by presenting a four-stage decision matrix extending from passive design to renewable energy generation and classifying each design decision with a "suitability code" system.

2.1. Passive Design Decisions

One of the most fundamental factors determining the energy performance of architectural design is the physical environmental conditions in which the building is situated. The literature frequently emphasizes that decisions made in the early stages of the design process, directly shape the building's total energy requirement [3,4,5]. In this context, the environmental context is not merely a physical backdrop but also a fundamental parameter defining the theoretical framework of energy-efficient design [6,7].

In hot-humid climate zones, high temperature and humidity are the guiding elements for design decisions. In this context, the most optimal relationship between buildings and their environment can be established by considering topography, solar radiation, and prevailing wind directions. In this climate type, orienting buildings to prevailing wind directions and placing them in locations that do not disrupt natural airflow is a priority design approach. Accordingly, it is suggested that structures be placed on the higher parts of south-facing slopes that receive cool winds. The relationship established with solar radiation, must be controlled. The optimal placement involves arranging the building's narrow facades to face east and west, while the wide facades are positioned along the north-south axis. Within this scope, the optimal solar orientation for the hot-humid climate zone is the placement of the building's wide surface towards the south and 18° southeast of south. The best orientation ranges should be between 10° southwest and 19° southeast, while acceptable orientation ranges should be between 19° southwest and 30° southeast [8,9]. Another prominent parameter in the relationship buildings establish with the sun and wind is the distance between buildings within the built environment. In hot-humid climate zones, it is important that the distances between buildings are arranged in a manner that will not obstruct each other's wind flow and will not interrupt the continuity of natural air corridors. Within this scope, the boundary values for distances between buildings and settlement recommendations for hot-humid climate zones are provided in Figure 1.

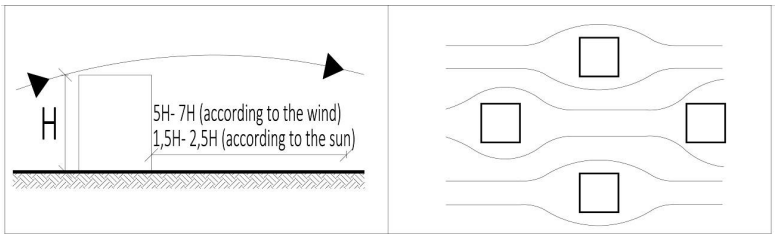


Figure 1. Distances between buildings and settlement recommendations according to wind and sun for the hot-humid climate zone [10]

Building form, geometric ratios, the volume-to-surface area relationship, and the arrangement of spaces side by side directly affect buildings' heat gains and losses [11]. Recent studies have also demonstrated that environmentally responsive façade geometries and performance-oriented architectural forms can significantly improve daylight efficiency, passive ventilation, and indoor thermal comfort in sustainable building design [56]. In this climate type, the optimum form factor is associated with increasing the surface-to-volume ratio to capture wind and facilitate cross-ventilation. For this reason, slender and horizontally elongated masses with their long side parallel to the prevailing wind direction are considered the most suitable solution [8,9]. Building form characteristics for hot-humid climate zones are presented in Table 1.

Table 1. Building form characteristics for hot- humid climate zones [3]

Building Layout	Configuration		
Detached Layout	Form	Form Factor (building depth / facade length)	
		Optimal Ratio	Maximum Ratio
	Freestanding, Elevated from Ground	1/1,7	1/3

The building envelope, which balances indoor comfort with variable outdoor climatic conditions, functions as a critical filter in hot-humid climate zones for reducing heat gains and maintaining a cool interior. For transparent surfaces, large openings should be permitted on facades, but these openings must be supported by shading elements to prevent direct solar radiation. Recent studies have also emphasized that natural material selection can significantly improve indoor environmental quality, thermal comfort, and long-term sustainability performance by enhancing passive environmental regulation strategies within architectural design [55].

Table 2. Optimum time lag, orientation and color selection for opaque components, and recommended frame and glazing types for transparent components in hot–humid climates [11,12]

Opaque			Transparent	
Material Selection	Time Lag Duration and Direction	Color	Recommended Frame	Recommended Glazing
Low Heat Storage Capacity	Undesirable	Light colors on all surfaces	PVC, wood, or fiberglass	Double-layered glass. Matte-green, heat-mirror glass for solar control on the exterior, and clear glass on the interior.

Roofs, in terms of their configuration (sloped or flat) and the layer where insulation is positioned (hot–cold roof), play a critical role in hot-humid climates for keeping the building cool and enhancing natural ventilation. Under hot-humid climatic conditions, wide-eaved, pitched roofs constitute the most suitable solution for both rainwater drainage and facade shading. These types of roofs also facilitate air circulation beneath the roof, thereby allowing heated air to be expelled. Light-colored and reflective coatings on roof surfaces diminish surface temperatures by reflecting solar radiation. For insulation placement in this climate type, a cold roof system is recommended. The ventilated void left between the roof covering and the ceiling functions as a buffer zone, assisting in the removal of hot air from the interior [13].

In hot- humid climatic conditions, the primary goal of insulation applications is not so much to reduce heat losses, but rather to limit the transmission of solar radiation from exterior walls into the interior space and to prevent internal overheating. Consequently, insulation thickness is maintained at a lower level compared to colder climates. According to TS825:2024, the insulation thickness for climate zone 1 should be between 7-11 cm for exterior facades and between 8-12 cm for floor slabs in contact with the ground [15].

In hot-humid climate zones, to mitigate the adverse effects of climatic conditions on buildings, spatial organization should prioritize natural ventilation, shading, and cooling. In this regard, living spaces should be positioned on the north and northeast facades to benefit from morning and evening breezes; conversely, service areas (bathroom, toilet, storage, etc.) should be located on the west and southwest facades to protect interior spaces from direct solar load. Zones, thin and elongated plan types with shallow depths and significant lengths should be preferred in terms of

form factor. Ceiling heights should also be increased to facilitate air movement; if possible, common living areas should be planned with high volumes, while service areas should have low volumes [3,11].

In hot and humid climatic conditions, the type and placement of vegetation must be determined to protect buildings from direct solar radiation, guide prevailing wind directions to support natural ventilation, and reduce indoor temperatures through its shading effect. In this context, in hot-humid climate zones, evergreen tall-trunked trees should be preferred on the northern side for winter, deciduous tall-trunked trees on the eastern and western sides, and deciduous low-branched trees on the southern side. This strategy prevents the building from overheating during the hottest period and allows solar radiation to reach the building during the least hot period, providing passive heating to enhance indoor comfort and decrease energy consumption.

2.2. Passive Systems

Passive systems constitute a comprehensive set of strategic solutions aimed at ensuring thermal comfort through the design of the building envelope and spatial organization in a manner congruent with climatic data, without recourse to additional mechanical equipment or external energy sources [16,17]. These systems are predicated upon the principle of collecting, storing, and distributing environmental inputs such as solar radiation, wind, and natural air movements acquired from the external surroundings, either directly or indirectly, via building components; or, conversely, mitigating excessive heat gains through mechanisms of shading, natural ventilation, and evaporation [14]. Passive systems are categorized into two types: direct and indirect heating-cooling systems.

Direct heating-cooling systems are implemented in hot-humid climate regions through the use of south-facing windows and skylights. While south-facing windows can provide limited heat gain during winter, they should be utilized in conjunction with solar control elements, given their potential to cause excessive radiation and heat gain for the majority of the year. Skylights, when positioned to create a chimney effect, contribute to natural ventilation and indirect cooling by enabling warm air to rise and be expelled externally. Indirect heating-cooling systems are founded upon the principle of collecting solar radiation not by directly introducing it into the interior space, but rather by gathering it on surfaces with high thermal storage capacity, such as walls, water

bodies, or similar elements, and subsequently transferring it to the interior space with a specific time delay [18].

In hot-humid climate regions, the heat gain potential of trombe wall systems can engender a risk of overheating during the summer months due to the elevated levels of solar radiation. Conversely, during winter periods, trombe wall can retain the solar energy accumulated during daytime within its thermal mass and transfer it to the interior space at night, thereby providing a limited yet beneficial heating contribution. Under summer conditions, control strategies such as the employment of shading elements, the selection of glazing surfaces with low transmittance coefficients, or the utilization of movable insulation components are requisite to preclude excessive heat gain [21].

A solar wall comprises a metal surface on its exterior and a dark-colored wall surface with high thermal mass behind it. The wall absorbs and stores solar radiation, subsequently transmitting this energy to the interior space. In hot-humid climatic conditions, this system possesses the potential to support thermal comfort during winter months by providing limited heat gain. However, during summer months, a risk of overheating arises due to high solar radiation, which can generate undesirable thermal loads in interior spaces. Consequently, during the summer period, the solar wall system must be protected with shading elements, utilize movable insulation components, or be designed with ventilation openings to contribute to passive cooling [22].

Water wall systems, the energy stored during the day can offer a limited heating contribution during winter months, thereby supporting indoor thermal comfort. However, conditions of high relative humidity exacerbate evaporation from the water wall, thereby increasing the moisture load of the interior space and adversely affecting comfort conditions. In this climate, the limited effectiveness of evaporative cooling, alongside hygiene issues such as algae formation, microbial proliferation, and odor problems during prolonged use, also constitutes disadvantages of the system. To minimize these drawbacks, preventive measures against overheating, such as various solar control elements and movable insulation panels, must be employed within the scope of water wall systems [24].

A sunroom reduces heat losses during winter months by creating a buffer zone and provides limited solar gains. In hot-humid climates, its primary function becomes prominent during summer

months, contributing to the cooling of interior spaces by enabling cross-ventilation through openable facade elements. Nevertheless, to prevent overheating, it requires support from shading, natural ventilation, the selection of glazing with low permeability coefficients, the use of movable insulation elements, and mechanical exhaust systems when necessary [23].

Roof pond systems can contribute to cooling interior spaces in summer through nocturnal radiative cooling and evaporation. However, in hot-humid climates, due to high humidity, roof ponds increase the indoor relative humidity, limit nocturnal cooling effectiveness, and become disadvantageous from a hygiene perspective by leading to algae and microorganism formation. In this regard, to mitigate the adverse effects of high humidity in roof pond systems, shading elements or movable insulation covers that prevent overheating during the day must be utilized. To enhance nocturnal radiative cooling effectiveness, it is essential to leave the water exposed overnight and protect it from the sun during the day [25].

Double-skin facade systems limit heat losses during winter months by creating a buffer zone between the inner and outer skins. In hot-humid climates, especially during summer months, they enable the expulsion of hot air via the stack effect and reduce solar gains. When supported by appropriate shading strategies, they contribute to providing coolness in interior spaces and reducing energy consumption [19,20].

2.3. Active Systems

Active heating and cooling systems rely on the use of mechanical and electrical equipment to ensure indoor thermal comfort and require energy consumption. In hot-humid climate regions, reducing cooling loads and ensuring humidity control are among the primary objectives of system design. Solar collectors provide an efficient energy source, particularly for domestic hot water production and low-intensity heating. When positioned on the roof or south facades of a building, solar collectors directly absorb sunlight and transfer energy to storage tanks via a heat-transfer fluid [26].

Heat pump systems are active heating/cooling systems that perform heat transfer using electrical energy and can utilize air, water, or ground temperatures as sources. Air-source heat pumps can perform both cooling and dehumidification functions during summer months; as there are no large temperature differences, efficiency remains relatively high throughout the summer period [27]. In

hot-humid climates, as the system's cooling capacity is prioritized due to humidity and high temperatures, water-source systems exhibit a limited effect. Ground-source systems are particularly suitable for increasing energy efficiency and assisting with humidity control in interior spaces during summer. These systems offer a highly efficient and sustainable solution against temperature and humidity fluctuations [28].

Condensing boilers are high-efficiency heating systems capable of transferring latent heat to the boiler water by condensing the water vapor within the flue gas. In hot-humid climate regions, under conditions where heating requirements are limited, the condensation technique minimizes system energy consumption and maximizes existing heat gain. However, in these climates, as the primary priority for ensuring indoor comfort is cooling and humidity control, condensing boilers are predominantly utilized as supplementary systems to provide low-intensity heating during winter months. When integrated with appropriate control mechanisms, the system not only enhances energy efficiency but also contributes to maintaining indoor comfort under excessive humidity conditions [29].

Absorption cooling systems are active systems designed to provide cooling using thermal energy (such as solar energy, waste heat, or low-temperature steam) instead of electrical energy. In hot-humid climates, given the prevalence of high temperature and relative humidity conditions indoors, absorption systems optimize indoor comfort by performing both cooling and dehumidification functions [30,31].

Evaporative cooling systems are passive, low-energy consumption air conditioning technologies that provide indoor comfort by cooling the ambient air through the principle of water evaporation. In hot-humid climates, evaporative cooling systems offer advantages such as low energy consumption, simple maintenance, and the use of renewable water resources. However, in the system's design, factors such as airflow optimization to prevent performance loss during periods of high relative humidity, selection of fill media, and maintenance schedules must be meticulously considered [32,33].

HVAC systems are integrated systems designed to energy-efficiently meet a building's heating, cooling, and ventilation requirements. In hot-humid climate regions, due to the prevalence of high temperature and relative humidity conditions indoors, HVAC systems primarily perform cooling

and humidity control functions. Indoor environmental quality is directly associated not only with thermal regulation, but also with ventilation performance, humidity control, air movement, and user comfort conditions within high-performance buildings [57]. In this context, when integrated with efficient fans, cooling units, air handling units with dehumidification capacity, and automation-controlled sensors, the performance of HVAC systems in hot-humid climates is optimized [34].

2.4. Energy Production Systems

Photovoltaic (PV) systems are renewable energy technologies that convert sunlight directly into electrical energy. In hot-humid climates, the efficiency of PV systems can be particularly affected by high temperature and humidity conditions. While high temperatures can reduce the electrical efficiency of PV cells, the accumulation of humidity and air pollution can impact long-term performance. The electrical performance of photovoltaic systems is strongly dependent on operating temperature conditions, and increasing surface temperatures may significantly reduce overall system efficiency and power output [58]. Therefore, in PV system design, factors such as panel tilt, orientation, natural cooling, and regular maintenance are critically important. Furthermore, since the annual sunshine duration is typically high in hot-humid regions, PV systems possess significant energy production potential and are capable of supporting electricity demand [37].

Wind turbines are renewable energy systems that convert the kinetic energy of the wind first into mechanical energy and then into electrical energy. Medium and small-scale wind turbines are utilized in buildings and can be installed in suitable areas such as gardens or rooftops. At the design stage, evaluating the sufficiency of wind speed and changes in direction is critically important for optimizing the turbine's energy production capacity [38,39].

Cogeneration and trigeneration systems are integrated systems that offer high energy efficiency compared to conventional single-purpose production systems by providing both electricity and thermal energy production from a single fuel source. In trigeneration systems, the generated heat can also be directed to cooling needs, being utilized in air conditioning or industrial processes. In hot-humid climates, cogeneration and trigeneration systems must be optimized specifically to meet cooling and dehumidification requirements. The system reduces CO_2 emissions and minimizes energy consumption by transferring waste heat from exhaust gases to cooling cycles. In this

context, trigeneration systems in hot-humid climates offer both an energy-efficient and environmentally friendly solution for buildings with high electricity demand and intense cooling requirements [40,41].

3. METHODOLOGY

This study adopts a structured, multi-stage, and performance-oriented methodological framework for the development and evaluation of a Net Zero Energy Building (NZEB) design model specific to hot and humid climate regions. The methodological approach is designed to ensure scientific rigor, methodological transparency, and repeatability, and directly addresses limitations identified in previous NZEB studies, particularly regarding the clarity of decision-making processes and simulation-based validation.

The research design is based on an integrated methodological approach that combines a systematic literature review, the development of a climate-responsive decision-making framework, and dynamic energy simulations. The overall workflow of the study is structured into three interconnected stages: (i) establishment of the NZEB design decision framework, (ii) application of this framework to a representative sample building, and (iii) quantitative performance evaluation through simulation-based analyses. This structure simultaneously enables the development of a theoretically grounded model and its empirical validation (Figure 2).

In this context, a four-stage decision-making model has been developed to systematically guide NZEB design processes under hot and humid climate conditions. This model consists of complementary and sequentially operating components: passive design strategies, passive system integration, active system optimization, and the use of renewable energy technologies. This staged structure reflects the hierarchical logic of energy-efficient building design, prioritizing energy demand reduction before system optimization and energy generation.

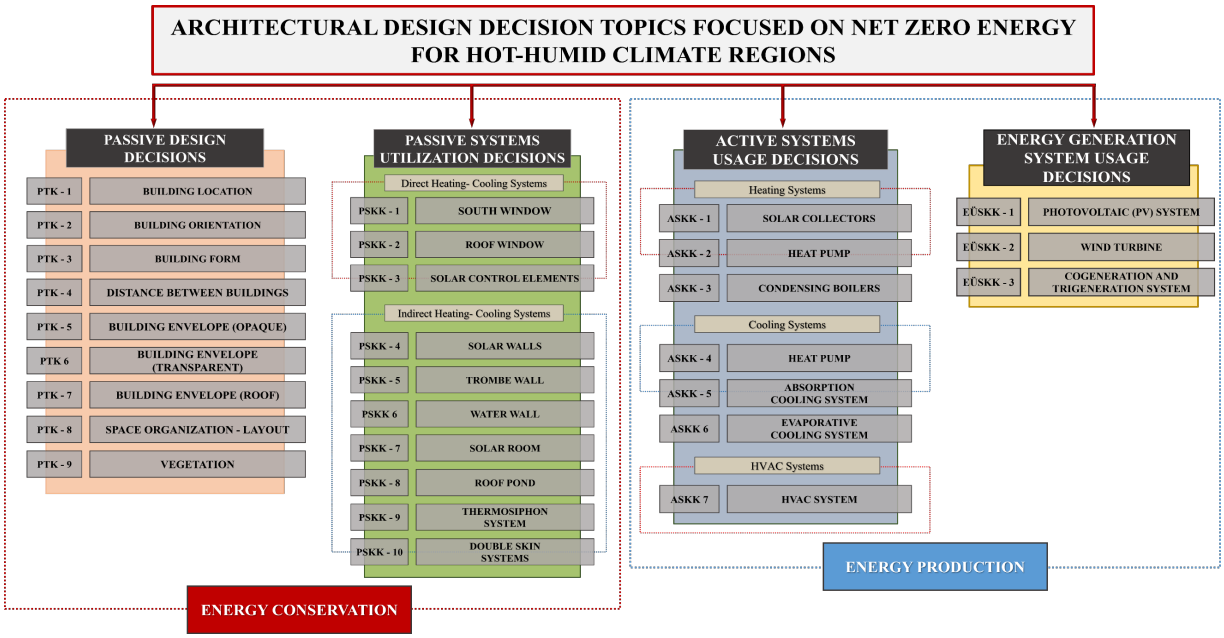


Figure 2. Flowchart of zero energy-oriented architectural design decision topics for hot-humid climate regions.

The development of the decision-making framework was based on a systematic and selective literature review. During this process, peer-reviewed journal articles, national standards, and current, high-impact studies focusing on NZEB applications in hot and humid climates were primarily evaluated. The obtained design parameters were analytically classified according to their functional roles in building energy performance. This classification facilitated the creation of a structured knowledge base to support the subsequent decision-making process.

To address ambiguities frequently encountered in the literature, each design parameter was analyzed within a multi-criteria evaluation approach. This evaluation was based on three key indicators: (i) impact on energy performance (reducing effect on heating and cooling loads), (ii) contribution to indoor thermal comfort, and (iii) suitability for hot and humid climate conditions (Figures 3-6). As a result of this analysis, a three-level decision coding system was developed: high suitability, conditional suitability, and low suitability. This system offers a transparent, systematic, and repeatable evaluation logic, constituting one of the main methodological contributions of the study.

The applicability of the proposed framework was tested using a detached residential building located in Antalya, a province representing Turkey's hot and humid climate region. To ensure comparability between scenarios, building geometry, orientation, spatial organization, and usage

profiles were kept constant. Internal gains were defined according to standard residential values, a split air conditioner was chosen as the HVAC system, and COP values of 2.35 for heating and 1.8 for cooling were used to represent system performance.

Dynamic energy simulations were performed using DesignBuilder v7.0.2 software. All input parameters were explicitly defined to ensure methodological repeatability. In this context, the thermal transmittance values of the building envelope (U-values compliant with TS825), glass properties and Solar Heat Gain Coefficient (SHGC), insulation thickness variations, HVAC system characteristics, and natural ventilation assumptions were detailed. Boundary conditions were standardized, indoor comfort temperatures were determined according to typical residential values, Antalya climate data was used, and simulations were run with an hourly time step.

A scenario-based comparative analysis method has been adopted to quantitatively reveal the impact of design decisions on energy performance. Within this scope, three different scenarios were created. The first scenario represents the baseline condition, defined by a building envelope compliant with TS825 (Turkish Thermal Insulation Standard) and standard system components. In the second scenario, insulation thicknesses were increased, advanced glazing systems were used, and thermal transmittance values were reduced to improve building envelope performance. In the third scenario, performance-based selection and integration of passive systems (such as sunspaces, double-skin facades, and roof ventilation strategies) were implemented, and photovoltaic systems were included in the model for building-scale renewable energy generation.

The performance of each scenario was evaluated using quantitative indicators such as annual total energy consumption, heating and cooling loads, energy use intensity (kWh/m^2), renewable energy generation, and net energy balance. In this study, Nearly Zero Energy Building (NZEB) performance was defined as the condition where annual on-site energy generation is equal to or greater than the total annual energy consumption. This definition allows for a holistic evaluation of the energy balance at the building scale.

In conclusion, this study, unlike the existing Nearly Zero Energy Building (NZEB) literature, presents a climate-specific, decision-oriented design framework; it proposes a transparent evaluation system and a hierarchical integration approach (passive → active → renewable). The proposed methodology not only produces performance results but also serves as a systematic and

repeatable decision support tool for researchers and practitioners working in hot and humid climate regions.

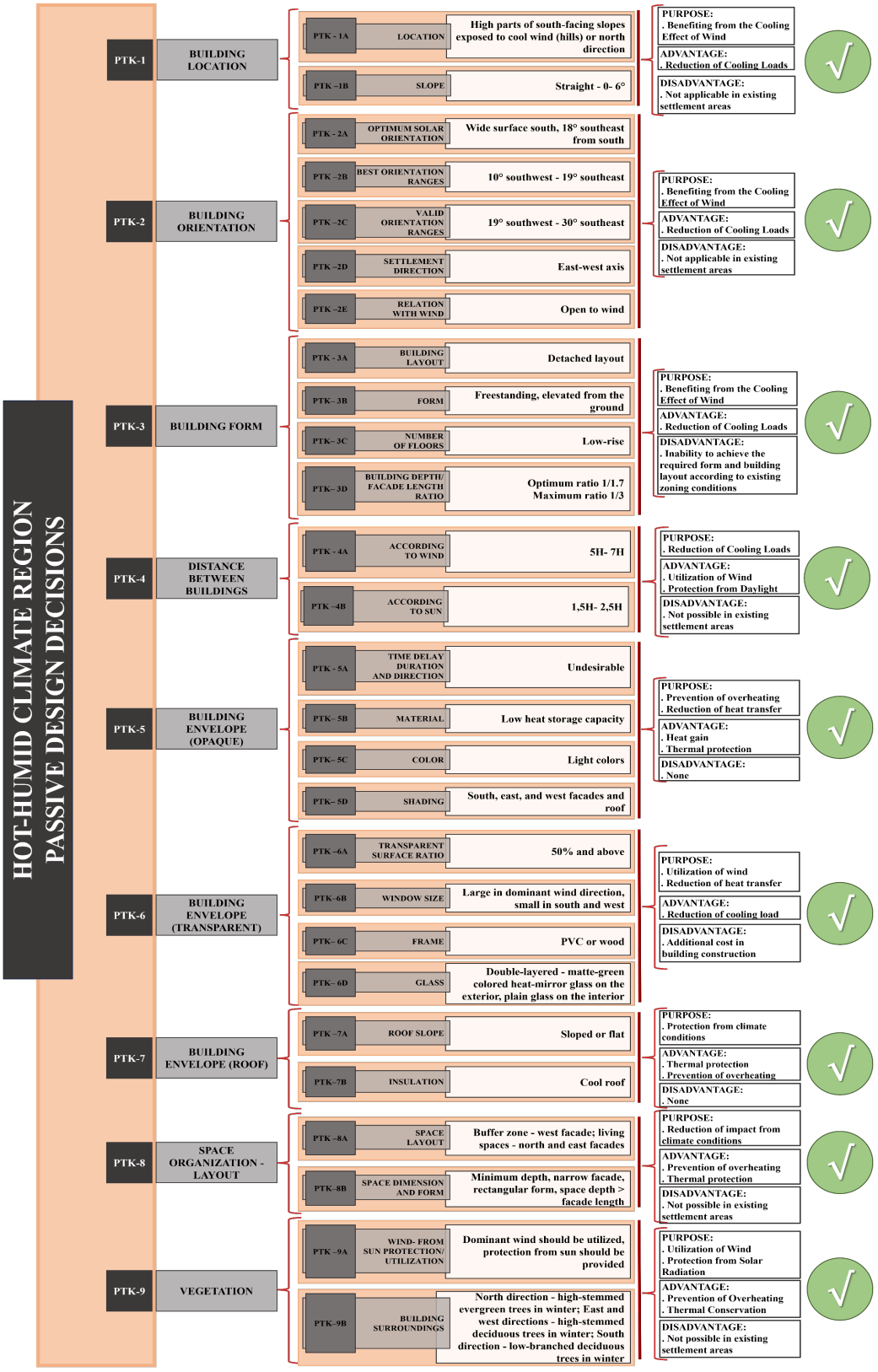


Figure 3. Passive design decisions for the hot-humid climate region

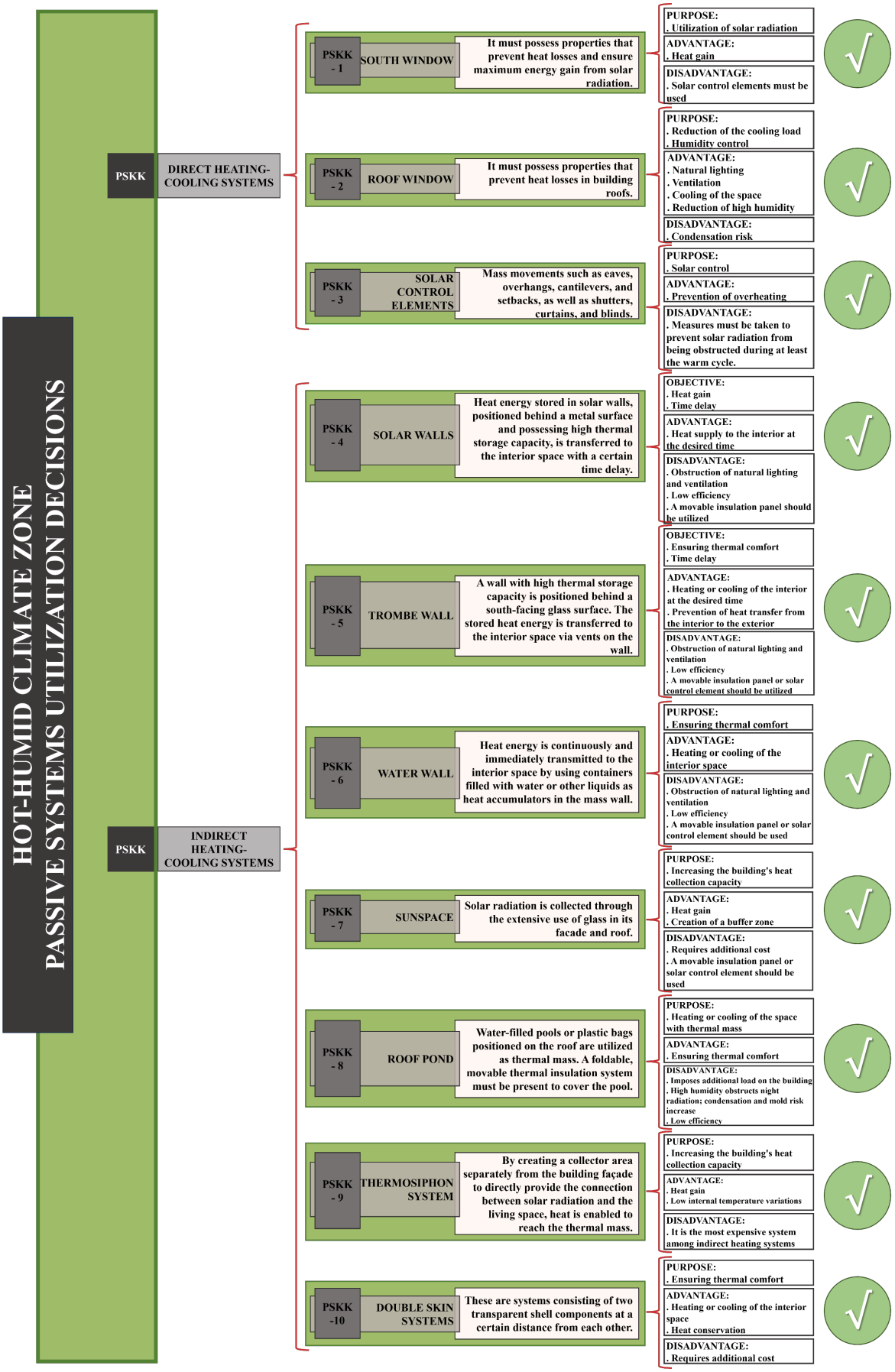


Figure 4. Decisions regarding the use of passive systems for the hot-humid climate region

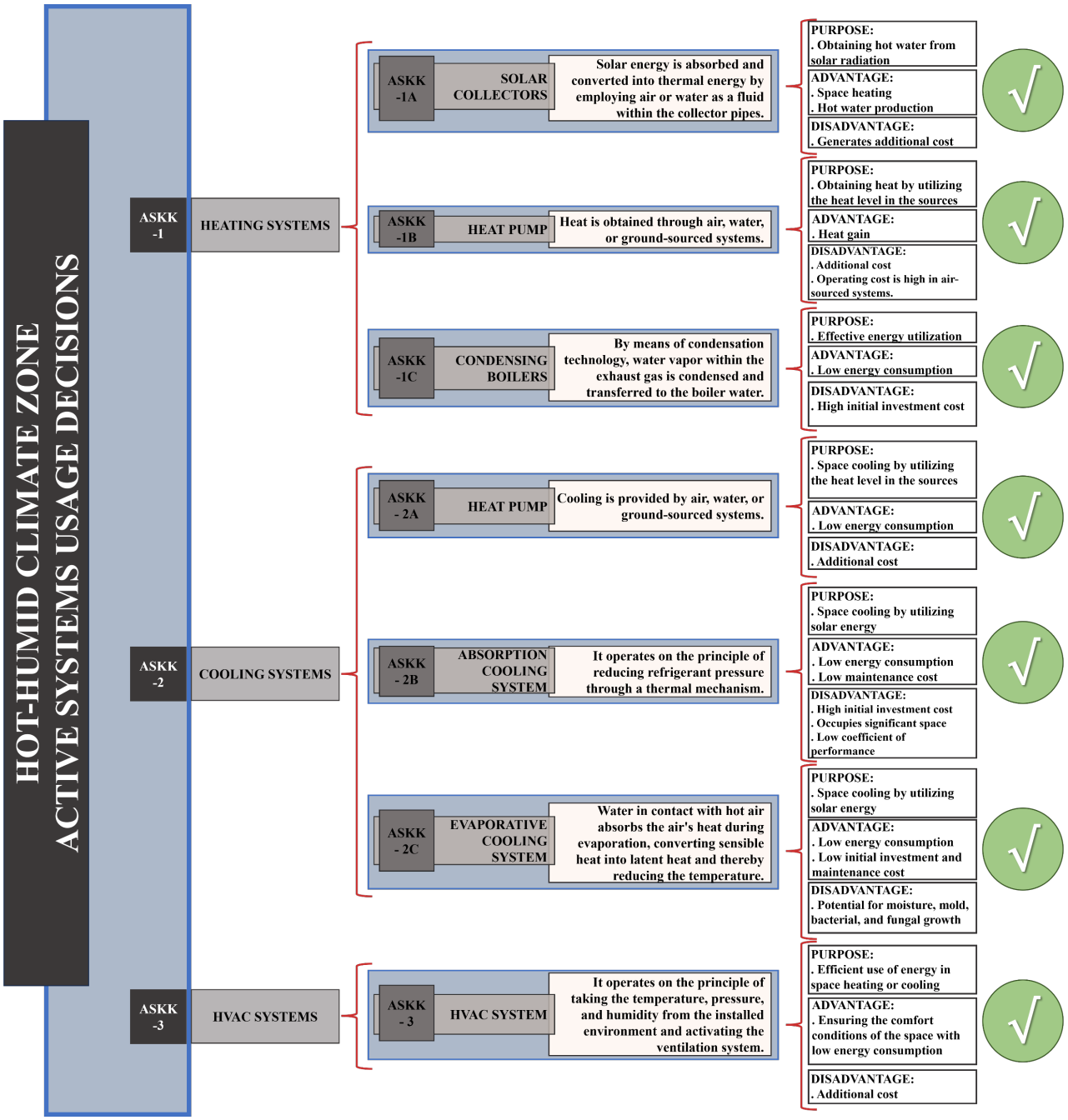


Figure 5. Decisions regarding the use of active systems for the hot-humid climate region

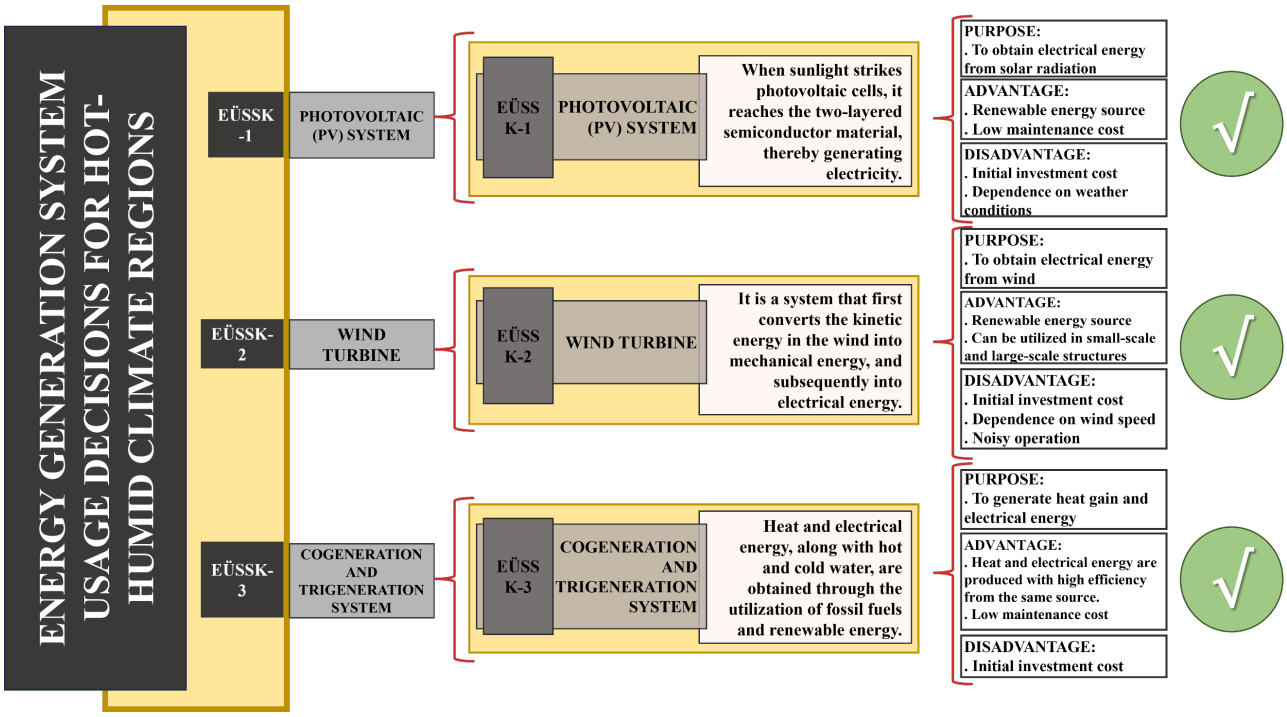


Figure 6. Decisions regarding the use of energy production systems for the hot-humid climate region

4. ANALYSIS STUDY

Antalya province is located in the west of the Mediterranean region in southern Turkey and exhibits hot-humid climate characteristics. According to TS 825:2024, Antalya is situated in climate zone 1. Although cooling loads account for the largest share of energy consumption in hot-humid climate regions, heating loads also represent a significant portion, albeit smaller, during winter months. Therefore, due to the necessity of taking measures for both heating and cooling, the study was conducted specifically for the hot-humid climate region.

4.1. Creation of the Base Model

For the building designed within the scope of this study, the following design decisions were made for the building conceived as the base model, based on the passive design decisions presented in Figure 2. The design decision step to which each adopted decision relates is indicated in parentheses.

- The building has been positioned on a flat terrain (PTK-1).
- The building has been oriented on an east-west axis such that its broader facade faces south (PTK-2A-2D).

- The building has been designed as a detached structure, elevated from the ground, with a ground floor plus two upper floors (G+2) (PTK-3A-3B-3C). The building depth-to-facade length ratio has been designed to be 1/1.7, which is the optimum ratio (PTK-3D).
- In the building envelope, the U-values for roof, opaque, and transparent surface components have been defined in accordance with TS825:2024 Zone 1 standards (PTK-5) (Table 3). Cellular concrete, possessing low heat storage capacity and low thermal conductivity, was selected for the opaque components. White paint was utilized on the facade (PTK-5B-5C). The transparent surface ratio in the building envelope has been defined as 50% for the north facade and 30% for the south facade. The Solar Heat Gain Coefficient (SHGC) value for the transparent surfaces has been determined as 0.697. Wooden material has been specified for the window frames (PTK-6). The building's roof has been designed as a hip roof with a 30% slope in two directions. The roof eaves are 50 cm, and the roofing material has been specified as Marseille tiles (PTK-7).
- In the spatial organization, buffer spaces have been located on the west facade, while other spaces are positioned on the north and south facades. Space depths have been kept shallower than the facade length (PTK-8).
- LED luminaires have been chosen as the lighting system in the building, and a split air conditioning system has been preferred for heating and cooling. Electricity has been assumed as the energy source, and the Coefficient of Performance (CoP) values, defined by the program as standard values, are taken as 2.35 for heating and 1.8 for cooling.

Table 3. Maximum U-values for opaque and transparent components in the building envelope for zone 1 according to TS825:2024 [15]

Wall - UD (W/m2K)	Roof - U-value (W/m²K)	Floor - U-value (W/m²K)	Window - U-value (W/m²K)
0,45	0,35	0,40	1,8



Figure 7. Base model floor plans

4.2. Energy Analysis Execution

Within the scope of this study, energy simulations were performed using DesignBuilder v7.0.2 software, which is based on EnergyPlus 9.4. The TMYx 2009-2023 package was utilized as climate data. The year 2024 was selected as the simulation year.

In the residential building designed for the purpose of comparing the energy efficiency improvements realized in this study, the building orientation, structural order, number of floors, spatial organization, and space dimensions were kept constant. In this context, three distinct scenarios were created to measure the impact levels of improvement applications aimed at energy efficiency within the scope of the study. In Scenario 1, the building envelope was formed based on the thermal transmittance coefficients defined in TS 825:2024 and accepted as the base model. Scenario 2 was formulated by implementing improvements in the opaque, transparent, and roof components of the building envelope. The layers and thermal transmittance coefficients applied in Scenario 1 and Scenario 2 are presented in Table 4. In Scenario 3, each system from the passive systems usage decisions table provided in Figure 3 was integrated into the building individually, their energy efficiencies were compared, and the systems providing the highest efficiency were selected. In this scope, the combination of a roof window, a sunroom, and a double-skin system

was determined to deliver the best performance. The roof window was placed on the north side of the roof, above the gallery void, thereby reducing the building's cooling load through natural ventilation. On the building's south facade, a sunroom system was applied to the balconies, and a double-skin system was implemented on the walls. To prevent heating of the building in the least warm cycle and overheating in the warmest cycle, solar control elements were integrated into both systems. Finally, in the building where energy consumption was minimized, 7,20 m x 4,70 m PV panels were added to the south-facing surface of the roof to enable the necessary energy to be obtained from renewable energy sources, thus ensuring the building attained net-zero energy building standards. The obtained results are presented in Table 5.

Table 4. Materials used in the building envelope and U-values

Envelope Element	Layers (Scenario 1)	U-value (W/m²K)	Layers (Scenario 2)	U-value (W/m²K)
Exterior wall	Paint + gypsum plaster + cement plaster + 20 cm aerated concrete wall + 3 cm rock wool thermal insulation + cement plaster + fine plaster + paint	0,45	Paint + gypsum plaster + cement plaster + 20 cm aerated concrete wall + 10 cm rock wool thermal insulation + cement plaster + fine plaster + paint	0,24
Ground floor slab	15 cm reinforced concrete slab + 6 cm XPS thermal insulation + 7 cm screed + wooden floor covering	0,40	15 cm reinforced concrete slab + 6 cm XPS thermal insulation + 7 cm screed + wooden floor covering	0,40
Roof slab	10 cm rock wool thermal insulation + roof covering	0,35	16 cm rock wool thermal insulation + roof covering	0,24
Glazing type	Low-e double glazing (6+13+6) (SHGC: 0.634)	1.8	Low-e triple glazing with green tint and krypton gas filled cavity (SHGC: 0.22)	0,687

Table 5. Comparison of Energy Consumption Data for the Generated Scenarios

Parameters	Scenario 1 (Base Model)	Scenario 2 (Envelope Improvements)	Scenario 3 (Passive Systems + Energy Production Systems)
Annual total energy consumption	11773,48 kWh	9872,56 kWh	8371,64 kWh
Electricity consumption per total area	82.77 kWh/m²	69.74 kWh/m²	59.12 kWh/m²
Annual total heating load	1205,78 kWh	1265,84 kWh	509,94 kWh
Heating load per total area	8.48 kWh/m²	8.94 kWh/m²	3.60 kWh/m²
Ratio of heating load to total energy consumption	%10,24	%12,82	%5,74
Annual total cooling load	4193,17 kWh	2569,64 kWh	1853,51 kWh
Cooling load per total area	29.48 kWh/m²	18.15 kWh/m²	13.09 kWh/m²
Ratio of cooling load to total energy consumption	%36,82	%26,02	%22,14
Annual total energy production			8413,78 kWh
Annual total energy demand			-42,14 kWh
Energy demand per total area			-0,298 kWh/m2

5. DISCUSSION

The climate-sensitive NZEB design framework developed in this study allows for a systematic and holistic evaluation of building energy performance in hot and humid climate conditions. The findings reveal that energy efficiency strategies, when considered not in isolation but within a phased and integrated system structure, are decisive for overall energy performance.

Upon examining the scenario analyses, it is observed that the second scenario, based solely on building envelope improvements, made a significant contribution to reducing energy consumption but was not sufficient on its own to achieve NZEB targets. In contrast, the third scenario, created with optimized passive systems and renewable energy integration, was determined to provide a significant improvement in energy performance and play a critical role in achieving a net energy balance. This clearly demonstrates that the NZEB approach inherently requires a multi-layered and integrated design process.

One of the most significant contributions of the developed decision-making framework is that it allows for the systematic classification and evaluation of design parameters. Unlike approaches frequently encountered in the literature, this study not only presents performance outputs but also proposes a transparent decision mechanism that explains how these outputs are achieved. The three-level suitability classification (high, conditional, low) reduces uncertainties in the design process and clearly demonstrates under which conditions different strategies should be applied.

Furthermore, the results indicate that passive design decisions should be prioritized in hot and humid climates. It has been determined that strategies such as solar control, natural ventilation, and limiting heat gains play a critical role in reducing energy demand. Active system optimization and renewable energy generation, on the other hand, stand out as complementary elements in balancing this reduced energy demand. This finding supports the validity of the "passive → active → renewable" sequence adopted in the proposed methodology.

Another important finding of the study is that design decisions cannot be evaluated independently of the climate context. Given that the same design strategy can produce different performance results under different climate conditions, the developed climate-specific decision framework offers more applicable and reliable results compared to generalized approaches in the literature.

However, the study also has some limitations. The fact that the analyses were conducted on a single sample building partially limits the generalizability of the obtained results. Furthermore, dynamic parameters such as user behavior and actual operating conditions were evaluated based on idealized assumptions within the simulation environment. Therefore, it is recommended that the methodology be further developed in future studies with different building types, usage scenarios, and real-time data integration.

6. CONCLUSION

This study aimed to develop a climate-sensitive and decision-oriented methodological framework for NZEB design in Hot and humid climate regions. Accordingly, a holistic design model was established through systematic literature review, a multi-criteria evaluation approach, and the integration of Dynamic energy simulations.

The developed methodology addresses the design process within a phased structure, encompassing Passive design, active system optimization, and renewable energy integration, supporting each phase with a systematic decision-making mechanism. This approach demonstrates that energy performance can be improved not only through technical solutions but also through the structured application of correct design decisions.

The study results indicate that singular design strategies are insufficient for achieving NZEB targets, and instead, an integrated and multi-layered approach is necessary. Specifically, optimizing passive systems to reduce energy demand and balancing this demand with renewable energy systems emerge as key determining factors in achieving NZEB performance.

The most significant contribution of this study to the literature is its proposal of a transparent, systematic, and repeatable Decision support framework that guides the design process, rather than merely an analysis approach presenting performance results. The developed three-level evaluation system enables designers to make informed choices among different strategies and reduces uncertainties in the decision-making process.

In conclusion, the proposed methodology offers a feasible and scalable approach for NZEB design in Hot and humid climate regions. This approach serves as a guide for both academic studies and implementation processes and can be further developed by adapting it to different climate regions and building types.

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Hikmet Alim: Conceptualization, methodology, investigation, data curation, formal analysis, software, visualization, writing – original draft preparation.

Figen Beyhan: Supervision, validation, methodology, review and editing, project administration.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] IEA (International Energy Agency). Energy efficiency 2021 – analysis and outlooks to 2030. International Energy Agency, Paris, France, 2021.

[2] Attia S, Gratia E, Herde AD, Hensen J. Simulation-based decision support tool for early stages of zero-energy building design. Energy and Buildings 2012; 49: 2–15.

[3] Olgyay V. Design with climate: bioclimatic approach to architectural regionalism. Princeton University Press, Princeton, NJ, US, 2015.

[4] Szokolay SV. Introduction to architectural science: the basis of sustainable design. Architectural Press, Oxford, UK, 2008.

[5] Hyde R. Climate responsive design: a study of buildings in moderate and hot humid climates. Taylor & Francis, London, UK, 2000.

[6] Steemers K. Energy and the city: density, buildings and transport. Energy and Buildings 2003; 35: 3–14.

[7] Givoni B. Climate considerations in building and urban design. John Wiley & Sons, New York, US, 1998.

[8] Barnett L, Barnett M. The passivhaus handbook: a practical guide to constructing and retrofitting energy-efficient homes. Green Books, Totnes, UK, 2017.

[9] Sharif HZ, Leman AM, Krizou AN, Al-Tarawneh MTA, Subbiah M, Al-Farsi M. Analysis of nearly zero energy residential building in Muscat. Journal of Thermal Engineering 2020; 6(3): 346–358.

[10] Demir S. Ilıman nemli iklim bölgesi için tasarlanan konut yapısında değişken yapı kabuğu performansının değerlendirilmesi. MSc Thesis, Yıldız Technical University, Istanbul, Turkey, 2017.

[11] Kısa Ovalı P. Türkiye iklim bölgeleri bağlamında ekolojik tasarım ölçütleri sistematiğinin oluşturulması: Kayaköy yerleşmesinde örneklenmesi. PhD Thesis, Trakya University, Edirne, Turkey, 2009.
[12] Ayçam İ, Utkutuğ G. Farklı malzemelerle üretilen pencere tiplerinin ısıl performanslarının incelenmesi ve enerji etkin pencere seçimi. VII Ulusal Tesisat Mühendisliği Kongresi, İzmir, Turkey, 2005.
[13] Orhon İ, Küçükdoğu MŞ, Ok S. Doğal iklimlendirme. Toplu Konut İşletmesi Proje Planlama Tasarım El Kitabı. TÜBİTAK YAE, Ankara, Turkey, 1988.
[14] Kaya GN, Beyhan F, İlerisoy ZY, Cudzik J. Evaluation of machine learning applications in building life cycle processes for energy efficiency: a systematic review. Energy Reports 2025; 13: 4900–4916.
[15] Turkish Standards Institution (TSE). TS 825 thermal insulation requirements for buildings. Turkish Standards Institution, Ankara, Turkey, 2024.
[16] Butera FM. Principles of passive solar building design. In: Santamouris M (Ed.). Advances in building energy research. Earthscan, London, UK, 2010.
[17] Weber W, Yannas S (Eds.). Lessons from Vernacular Architecture. Earthscan/Routledge, London, UK, 2013.
[18] Santamouris M. Passive cooling of buildings. Earthscan, London, UK, 2005.
[19] Lakot Alemdağ E, Beyhan F. A research on construction systems of double skin facades. Gazi University Journal of Science 2017; 30(1): 17–30.
[20] Lakot Alemdağ E. Saydam yalıtımlı yapı dış kabuğu ısıl performansının deneysel incelenmesi. PhD Thesis, Karadeniz Technical University, Trabzon, Turkey, 2013.
[21] Kundakcı Koyunbaba B. Model bir PV/T trombe duvarın enerji analizi. PhD Thesis, Ege University, Izmir, Turkey, 2010.
[22] Kallioğlu MA. Güneş duvarının performansına etki eden parametrelerin sayısal ve deneysel olarak incelenmesi. PhD Thesis, Batman University, Batman, Turkey, 2021.
[23] Yüre T. Güneş enerjisinden edilgen sistem yararlanmada güneş odası ekleme yönteminin iç ortam sıcaklığına etkisinin incelenmesi: İstanbul örneği. PhD Thesis, Yıldız Technical University, Istanbul, Turkey, 2007.
[24] Elshinnawy P. An approach for comparing the energy efficiency of waterwall systems in an office space: case studies in Istanbul and Stockholm. MSc Thesis, Yasar University, Izmir, Turkey, 2018.

[25] Uslusoy S. Yenilenebilir enerji kaynakları kullanan enerji etkin binaların yapı bileşeni açısından irdelenmesi. MSc Thesis, Dokuz Eylul University, Izmir, Turkey, 2012.
[26] Duffie JA, Beckman WA. Solar engineering of thermal processes. John Wiley & Sons, Hoboken, NJ, US, 2013.
[27] Alshehri F, Beck S, Ingham D, Ma L, Pourkashanian M. Techno-economic analysis of ground and air source heat pumps in hot/dry climates: Saudi Arabia as a case study. Journal of Building Engineering 2019; 26: 100825.
[28] Chanchayanon T, Chaiprakaikeow S, Jotisankasa A, Inazumi S. Optimization of geothermal heat pump systems for sustainable urban development in Southeast Asia. Smart Cities 2024; 7(3): 1390–1413.
[29] Chen Q, Finney K, Li H, Zhang X, Zhou J, Sharifi V, Swithenbank J. Condensing boiler applications in the process industry. Applied Energy 2012; 89(1): 30–36.
[30] Dincer I, Rosen MA. Exergy: energy, environment and sustainable development. Elsevier, Oxford, UK, 2007.
[31] Li F, Dai Y, Wang RZ. Solar-driven absorption cooling systems: a review on system configurations and performance optimization. Renewable and Sustainable Energy Reviews 2020; 119: 109586.
[32] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 2009; 13(2): 318–345.
[33] Al-Tamimi N, Abdullah S, Ismail WIW. Performance evaluation of evaporative cooling systems in hot and humid climates. Energy and Buildings 2021; 251: 111327.
[34] Anand S, Che D, Zhang X, Krarti M. Review of energy-efficient HVAC technologies for sustainable buildings. International Journal of Science and Technology Research Archive 2024; 6(2): 12–20.
[35] Huang Y, Liu J, Yang H. Performance analysis of photovoltaic systems under tropical climates. Renewable Energy 2021; 163: 1234–1247.
[36] Li W, Chen X, Wang S. Impact of ambient temperature and humidity on photovoltaic panel efficiency in hot–humid regions. Solar Energy 2020; 207: 569–578.
[37] Kaya GN, Beyhan F. Yapılarda güneş enerjisi sistem uygulamalarının enerji verimliliği bağlamında değerlendirilmesi. Tesisat Mühendisliği 2025; 33(208): 31–40.
[38] Manwell JF, McGowan JG, Rogers AL. Wind energy explained: theory, design and application. Wiley, Chichester, UK, 2010.

[39] Burton T, Sharpe D, Jenkins N, Bossanyi E. Wind energy handbook. Wiley, Chichester, UK, 2011.
[40] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. Wiley, New York, US, 1996.
[41] Ibrahim M, Dincer I, Rosen MA. Performance evaluation of trigeneration systems in hot and humid climates. Applied Thermal Engineering 2020; 178: 115525.
[42] Al-Saadi A, Al-Badi AH, Al-Rawas G, vd. Transforming a school building into zero-energy status: A feasibility study for hot-dry, hot-humid, and warm-humid climates. Solar Energy 2023; 264: 112050.
[43] Sarir P, Sharifzadeh M. Application of passive and active scenarios to a residential building in a dry and hot climate to achieve a positive energy building (PEB). Heliyon 2024; 10: e30694.
[44] Mohammadi A, Mousavi SM. Feasibility study of net-zero energy residential buildings in hot and humid climates: A case study of Iran. Jurnal Teknologi 2022; 84(2): 71-91.
[45] Abuimara T, Haddad M, Aldhaheri A, vd. House of the Future: Designing a Net-Zero Energy Housing Archetype for Emirati Families. Environmental Science and Sustainable Development 2025; 10(3): 1224.
[46] Ibrahim MM, Suarez-Lopez MJ, Hanafy AA, William MA. Optimizing NZEB performance: A review of design strategies and case studies. Results in Engineering 2025; 25: 103950.
[47] Ohene E, Krarti M, Chan APC, Hsu SC, Ansah MK. Optimal design guidelines for net zero energy residential buildings in cooling-dominated climates: Case study of Ghana. Building and Environment 2024; 260: 111685.
[48] Kaitouni SI, Pfafferott J, Jamil A, Ahachad M, Brigui J. A holistic digital workflow methodology to shifting towards net zero energy urban residential buildings in a semi-arid climate. Solar Energy 2023; 263: 111959.
[49] Kaitouni SI, Sangkyu P, Mghazli MO, vd. Design parameters influencing the energy performance and indoor comfort of net zero energy building "NZEB" designed for semi-arid urban areas: Digital workflow methodology, sensitivity analysis and comparative assessment. Solar Energy 2024; 268: 112264.
[50] Salem E, Elwakil E, Hegab M. A Regional Investigation of Near-Zero Energy Buildings: Assessing the Impact of PV Integration and Building Design. 42nd International Symposium on Automation and Robotics in Construction (ISARC 2025), 2025.

[51] Rezaee R, Vakilinezhad R, Haymaker J. Parametric framework for a feasibility study of zero-energy residential buildings for the design stage. Journal of Building Engineering 2021; 35: 101960.
[52] Diker B, Yazıcıoğlu F. Technical and financial analysis of energy efficiency measures taken for transforming of existing qualified residential buildings into nZEBs: The case of Istanbul. Journal of the Faculty of Engineering and Architecture of Gazi University 2025; 40(4): 2219-2236.
[53] Acar U, Kaska O. Energy and economical optimal of Nzeb design under different climate conditions of Türkiye. Journal of Building Engineering 2022; 60: 105103.
[54] Takva C, Caliskan BN, Cakici FZ. Net Positive Energy Buildings in Architectural Context. Journal of Asian Scientific Research 2022; 12(3): 135-145.
[55] Amirov N, Küçüktüvek M. Ahşap yapıların biyofilik tasarımla entegrasyonu: Doğaya dönüş ve sürdürülebilirlik. Kent Akademisi 2025; 18(1): 520–539.
[56] Amirov N, Aghayeva N. Mathematical approaches in contemporary architectural practices: The case of Baku. Kent Akademisi 2025; 18(5): 2483–2519.
[57] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. Building and Environment 2011; 46(4): 922–937.
[58] Skoplaki E, Palyvos JA. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy 2009; 83(5): 614–624.
[59] de Dear R, Xiong J, Kim J, Cao B. A review of adaptive thermal comfort research since 1998. Energy and Buildings 2020; 214: 109893.