# From Building to Neighborhood: Investigating the Use of Artificial Intelligence and Machine Learning in Energy Management of Zero Energy Urban Neighborhoods Using a Bibliometric Approach (2020-2025)

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**Net Zero Energy Buildings (NZEBs) and nearly Zero Energy Buildings (nZEBs) have evolved from individual building concepts toward broader applications at the urban neighborhood scale. This paper presents a bibliometric analysis of energy management practices in zero energy urban neighborhoods, focusing on emerging research trends over the period 2020–2025. Using VOS viewer software, we analyze 584 peer reviewed articles retrieved from major scientific databases. The study maps the co-occurrence of keywords, country level research activity, and author collaboration networks. Results indicate exponential growth in publications from 2023 onward, driven by the convergence of zero energy concepts with artificial intelligence, machine learning, deep learning, and digital twins. Key thematic clusters include energy management systems, HVAC optimization, renewable energy integration, smart grids, and the Internet of Things. Geographically, research leadership has shifted from Europe and the United States (2021–2022) to Asian countries (China, India, South Korea, Japan, Iran) by 2023–2025. A persistent research gap is identified: zero energy neighborhood development in hot and humid climates, particularly in developing economies, remains severely underrepresented due to high upfront costs and long payback periods. The review synthesizes design hierarchies passive strategies first, followed by efficient active systems, then on site renewable generation and discusses the limitations of current AI applications, including data availability, generalizability, interpretability, and the absence of standardized benchmarks.**

***Keywords:*** *Net Zero Energy Building (NZEB), Nearly Zero Energy Building (nZEB), VOS viewer, Hot and Humid Climates, Cost-effective Strategies.*

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## 1. Introduction

The concept of NZEB (Net Zero Energy Building) was introduced as a radical approach to reducing energy consumption and greenhouse gas emissions in buildings [1, 2]. Its definitions have been actively discussed and examined worldwide over the past decade. The evolution of these definitions has been summarized and compared in numerous studies [2-4]. Although extensive research, initiatives, and policies regarding NZEB have been undertaken by many countries, organizations, and associations in recent years [4], the concept remains relatively new, and there is no definitive or universally accepted criterion for net zero energy. In practice, NZEB definitions vary in emphasis on specific descriptions depending on project goals and the values of the design team and building owner [3, 5]. The primary definitions originate from the European Union (EU) and the United States. The EU characterizes NZEB as a "building with very high energy performance," where the nearly zero or very low amount of energy required should be largely covered by energy from renewable sources, including "renewable energy produced on-site or nearby"[6, 7]. The term Net Zero Energy Building (NZEB) is primarily adopted by the U.S. Department of Energy (DOE) and the National Institute of Building Sciences (NIBS) to describe a building where the actual annual delivered energy is less than or equal to the renewable energy exported from on-site production. In contrast, nZEB (nearly Zero Energy Building) is the official term introduced by the European Union’s Energy Performance of Buildings Directive (EPBD), which defines it as a building with very high energy performance, where the nearly zero or very low amount of energy required should be largely covered by energy from renewable sources, including on-site or nearby generation.

The uniform definition of Zero Energy Building (ZEB) is clearly established in European Union countries [2, 8]. In the United States, the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) published an important definition of ZEB in response to the Energy Independence and Security Act of 2007[8-10]. According to this definition, a ZEB is "an energy-efficient building where, based on the energy source, the actual annual delivered energy is less than or equal to the renewable exported energy produced on-site." Additionally, three other definitions are provided for buildings with shared renewable energy sources: Zero Energy Campus (ZEC), Zero Energy Portfolio (ZEP), and Zero Energy Community (ZECo) [9] . Several acronyms related to ZEB exist, such as nearly, net, positive, and zero. To reduce confusion around the term "net," Net Zero Energy Buildings (NZEBs) have been adopted by the U.S. Department of Energy and the National Institute of Building Sciences (NIBS)[2, 10] as a replacement for Zero Energy Buildings. To avoid any misunderstanding, NZEB in this paper refers to nearly zero energy buildings, defined as residential or commercial buildings whose on-site energy needs are significantly reduced through improved efficiency and local renewable energy supply, resulting in a net zero energy balance [3]. According to this standard and the international standard EN 15603:2008, the energy rating calculation must only include energy consumption that "does not depend on occupant behavior, actual weather conditions, or other actual (environmental and internal) conditions"[7, 11]. The energy services considered in the calculation should include heating, cooling, ventilation, and domestic hot water for residential buildings [10, 12].

Kapsalaki and colleagues proposed a cost-effective design methodology for Net Zero Energy Buildings (NZEBs) at the early design phase. The proposed design approach incorporates variables spanning from building envelope characteristics to the building's energy systems and the related costs [13]. Christopher and his colleagues proposed a simplified method for building energy optimization during the early design stage [14]. Assion and his collaborators conducted a series of research studies on NZEB design [7, 15, 16]. They initially proposed a method for optimizing the combined design of renewable energy systems to meet the energy demand of a new Italian residential building, considering energy consumption for space heating and cooling, domestic hot water, and electrical appliances based on primary energy demand and investment cost. Subsequently, they presented an approach for the cost-optimal design of a new multi-zone residential building. This design approach was integrated with a multi-objective model predictive control of HVAC systems. They also used a typical Italian residential building to demonstrate multi-objective optimization of building envelope design aimed at minimizing energy consumption and cost across various climatic regions of Italy. Li and Wang focused on the impact of interactions between the building envelope and energy systems in NZEB design and proposed a multi-stage design optimization approach [17]. Then, they considered uncertainties in NZEB design optimization in another study [18]. Based on a dataset collected from a constructed residential building, Li and his colleagues proposed a comprehensive framework for identifying cost-effective designs for NZEBs [19]. Further research efforts in this field are ongoing. Delgarm and his collaborators conducted simulation-based optimization of building energy consumption in Iran [20]. Harkus and colleagues presented a cost-effective multi-criteria simulation-based optimization of NZEBs in Europe [21].

The concepts of cost-optimal energy efficiency and nearly zero-energy buildings (nZEB) have been introduced by this directive. Buildings must consume very little energy to approach the status of nearly zero-energy buildings, and the majority of this energy should be supplied from renewable sources [22]. The goal of nZEB is to reduce energy consumption in buildings by using efficient energy technologies and renewable energy solutions [1]. Wang and Zhao [23] investigated the impact of exterior walls and roofs with different heat transfer coefficients (U-values) on building energy consumption and found that improving energy efficiency in the building envelope significantly influences energy savings. Zhao and Du [24] aimed to achieve zero-energy educational buildings (nZEB) in China by optimizing national technologies and applying four recommended technologies across four major climate zones. They also determined that the total energy savings rate in very cold regions increased by 70.74% compared to current national standards, and nearly 60% of the total energy savings rate could be improved in cold areas.

Kalaycioglu and Yilmaz [25] identified single or combined measures to improve energy efficiency according to the proposed EPBD methodology. By analyzing the energy and cost implications of these measures, they found optimal cost and nearly zero-energy levels at the settlement scale. It was found that the analysis outcomes depend on countries' economic data, building regulations, and political and financial goals. Valancius and colleagues [26] presented a methodological approach addressing energy and environmental factors for achieving nearly zero-energy building (nZEB) levels in Lithuania's climatic conditions. Using this method, several energy efficiency improvement scenarios were applied in a case study. Results included initial energy savings and CO2 emissions over a reasonable 60-year period, along with the most suitable thermal insulation materials for energy and environmental performance. A four-star hotel located in Faro, Portugal, was used as a reference, and technical and economic analyses were conducted to determine nZEB levels in three European cities with different climates. Building energy modeling was conducted with DesignBuilder/EnergyPlus software, and energy efficiency improvement criteria with optimal costs were determined. Based on climatic and economic realities of the three cities, the most appropriate energy efficiency improvement measure was selected [27].

Several research studies on residential thermal comfort have highlighted the effects and general occupant preferences regarding sensations of being too warm or too cool [28]. The data gathered by AEDES, however, does not include direct measurements of thermal comfort inside buildings. Therefore, concerning thermal comfort and heat stress in Dutch residential buildings, various independent investigations have examined how heat and climate change affect vulnerable groups during heatwaves [29], as well as strategies for adapting to rising urban temperatures.

Around the same time, the European Directive 2018/844/EU was introduced in 2018. This directive paved the way for the release of a new standard, ISO 52016–1, which enables the assessment of overall building energy performance while balancing computational efficiency with simulation accuracy [30,31].

According to Nematchoua et al. (2021), a net-zero energy neighborhood is defined as a district that achieves zero net energy consumption on an annual basis. This means that the total energy used by the neighborhood over the course of a year equals the amount of renewable energy generated either on-site or, depending on the definition, from renewable sources. Such districts often emit fewer overall greenhouse gases during their operation compared to similar non-zero-energy neighbourhoods. They may still consume non-renewable energy for instance in winter and produce greenhouse gases, but during other seasons (e.g., summer) they offset this by reducing an equivalent amount of energy consumption and greenhouse gas emissions elsewhere [32]. Most zero-net-energy districts obtain half or more of their energy from the grid and return the same amount over the year. To date, net-zero energy neighborhood technology remains novel in many countries. Among various sectors (transport, industry, building, etc.), the building sector plays a particularly significant role in advancing energy efficiency goals worldwide [33].

For instance, Tonkoski et al. (2012) assessed voltage profiles in residential neighborhoods equipped with PV systems and quantified how system components influence voltage rise [34]. Fina et al. (2020) developed a model to determine the optimal economic potential of extensive rooftop PV systems within energy communities [35]. Ji et al. (2022) proposed a framework for optimizing both the design and operation of neighborhood-scale hybrid power systems that combine rooftop PV with waste biomass [36]. These works highlight that detailed generation data improves understanding of PV system performance by capturing fluctuations, thereby enabling better alignment of generation with demand. The performance and efficiency of neighborhood-level PV power generation are shaped by a range of factors, including external environmental conditions, internal system configurations, technical parameters, and other related aspects [37,38]. External environmental factors play a crucial role in determining PV system performance, encompassing solar radiation [39,40], temperature [39,40], and wind speed [41]. Furthermore, additional technical factors require attention, such as constant elements like system losses and inverter efficiency [42]. Urban morphology comprising building type, geometry (e.g., orientation), and density plays an essential role in shaping neighborhood PV generation [43]. Understanding the interactions among these factors is critical, as they collectively influence the performance of neighborhood PV systems and associated planning decisions. A holistic approach to understanding and managing these factors is essential for unlocking the PV energy potential within neighborhoods and ensuring optimal sustainable energy planning.

## 2. Scope

The main objective of this paper is to present a bibliometric analysis of energy management practices in zero-energy buildings and to extend this approach to zero-energy urban neighborhoods, with an emphasis on the role of Artificial Intelligence (AI) and Machine Learning (ML) technologies over the period 2020–2025. Using VOSviewer software, this study maps and analyzes emerging trends, keyword co-occurrence, author collaboration networks, and the geographical distribution of research. In Table I (in the appendix), a parametric comparison has been made regarding the research gap that this paper fills compared to previous studies, as well as the innovation of the paper.

## 3. Innovation and Research Gap

The innovation of this study lies in the fact that the time period examined is short and up to date, covering articles up to 2025—the most recent publications. This is because most previous bibliometric reviews are older and have focused on more general topics. This study has a relatively novel focus on both artificial intelligence and the neighborhood scale (not just the building level). Most previous works either focused solely on buildings or did not incorporate artificial intelligence and predictive algorithms. This paper introduces a reliable scientific roadmap. It addresses the research gap related to hot and humid climates although not entirely new and shows that almost no study exists that combines this climate context with AI.

First innovation: This study focuses on a short and emerging time window (2020–2025), which coincides with the peak development of machine learning and AI applications in zero-energy buildings.

Second innovation: It employs a bibliometric approach using VOSviewer to map the scientific structure of the field, including keyword co-occurrence, journal and document co-citation analysis, and concept density analysis.

Third innovation: It identifies a geographical shift in research leadership from Europe and the United States to Asian countries, offering a novel perspective on regional developments.

Fourth innovation: It identifies the thematic convergence of zero-energy buildings with concepts such as deep learning, introduced as a key and emerging trend.

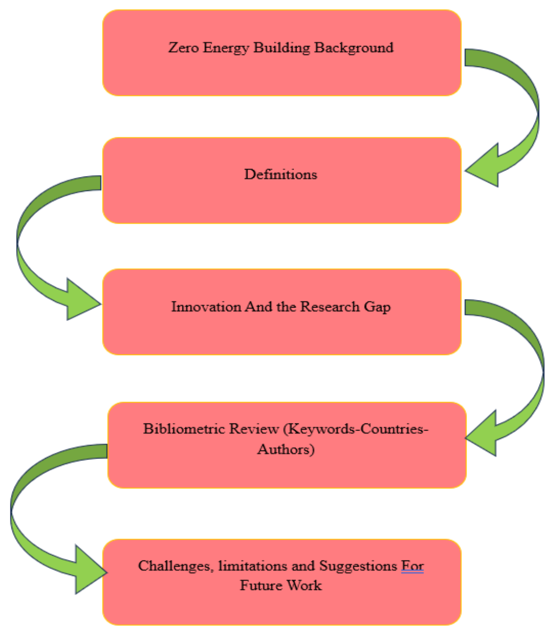



**Fig. 1.** A conceptual schematic of the review process in the present bibliometric study

In Figure 1, the schematic overview of this study is presented in various sections of the study. The various sections of the study are examined as follows: Section 1 (Introduction), Section 2 (Objective and background of the study), Section 3 (Research gap and Innovation), Section 4 (Various studies on the field of hot and temperate climate countries), Section 5 (Methodology) Section 6 (Results), Section 7 (Discussion), and Section 8 (Conclusion).

## 4. Hot and humid climates: challenges, passive strategies, and cost-effective pathways for NZEBs

Only 11 of these projects are located in hot and humid regions, and only three of them were selected in a report covering 30 NZEB buildings with sufficient technical data and energy performance information. Moreover, all three are from developed countries. The imbalance in NZEB development is mainly due to economic reasons, as high initial investments and long payback periods are major barriers for zero-energy buildings in developing regions [44]. Under these circumstances, it is crucial for developing countries to focus on passive strategies with relatively low initial investment and cost-effective strategies with shorter payback periods to promote NZEB development in hot and humid climates. Evaluating the cost-effectiveness of technologies used in net zero-energy buildings is especially important for developing regions [45]. Policies and incentives play a vital role in promoting NZEB development in hot and humid areas.

Buildings in tropical regions are often designed to enhance interaction between the indoor and outdoor climates, especially during seasons without air conditioning. In contrast, buildings in cold climates often emphasize a seamless building envelope system. Therefore, designing a chimney-free cooling system that utilizes passive features such as natural ventilation and daylighting to reduce building energy consumption is important. Indoor comfort criteria can also differ in naturally ventilated buildings. The "adaptive thermal comfort model" for naturally ventilated or mixed-mode environments is required for NZEBs in tropical climates [46,47] to maximize natural ventilation and save energy consumption. Since NZEBs interact more with the outdoor environment, they can significantly influence the selection of NZEB technologies and occupant comfort satisfaction [48-52]. People living in areas with significant environmental challenges often resist accepting unsuitable indoor environments and tend to support green technologies more [53].

An NZEB must first be an energy-saving building. The energy consumption of a building as a whole can be offset by renewable energy generated on-site or obtained nearby so that a balance is achieved between energy consumption and energy output. To clarify the research subjects and technical boundaries involved in NZEB assessment, Deng et al. (2014) [5] used a definition framework, equations, and graphics methods to describe the essential NZEB evaluation operating mechanisms, and proposed NZEB design elements, including energy-efficient measures, and their scope. The most widely accepted definition of NZEB consists of a defined framework, which includes different elements. Different participants can, therefore, select different components based on individual considerations of cost, local climate, environmental protection demand, or the feasibility of on-site renewable energy sources, following a common framework, and thereby establish specific definitions of different applicable criteria. Basic NZEB evaluation operating mechanisms are as shown in Figure 1, where essential elements include the building system, energy grid, and weighting system. To perform the calculations needed to assess whether the net zero targets can be met, NZEB requires the delineation of boundaries around the building system's on-site renewable energy. Within these boundaries, when an on-site renewable energy power system generates excess power, the building system will transmit excess energy to the power grid. Besides, the net energy obtained by the building system as a whole will reflect the selected design goals and weighting system. For instance, when "kWh usage" is multiplied by "unit power price", we can obtain "cost of power", or when "kWh usage" is multiplied by the "power/carbon footprint coefficient", we can obtain CO2 emissions. Finally, the supply can be compared with the weighted load to determine whether net zero balance can be achieved via the specific technological solution.

Figure 2 provides a detailed and conceptual view of how a net zero energy building (NZEB) operates. In Figure 1, the building system boundary is clearly defined and within it are two main components, namely "load" and "generation". The energy generated on site is first used to meet the building's internal needs and, if there is a surplus, is exported to external networks. Conversely, when internal generation does not meet the building's needs, energy is obtained from external sources such as grid electricity, district heating and cooling, natural gas, biomass and other fuels. The key point in this model is the use of a weighting system to assess energy demand and supply. This system can be defined in terms of kilowatt-hours, carbon dioxide emissions or other environmental and economic indicators. Through this weighting, energy consumption and generation are calculated in an adjusted manner to allow for accurate comparison and assessment. When the weighted supply is equal to or greater than the weighted demand, the building achieves NZEB status.

Figure 3 shows a conceptual and analytical diagram of the energy optimization path in buildings, which is particularly useful for understanding the process of moving from reference buildings to net zero energy buildings (NZEB). The horizontal axis of the diagram represents the energy load of the building (demand) and the vertical axis represents the amount of energy generated (supply). The diagonal dotted line, labeled "net zero balance line," marks the theoretical boundary between equal generation and consumption; the point at which the building achieves NZEB status. In this figure, three key points can be identified: the reference building with high energy consumption, the optimized design with reduced consumption, and the NZEB building that is at the equilibrium point. The horizontal distance between the reference building and the optimized design is labeled "energy efficiency," which indicates the amount of energy consumption reduction through optimization of the building's design, equipment, and operation. This reduction can be achieved through the use of advanced technologies in insulation, air conditioning, intelligent controls, and the use of materials with high thermal performance. The optimized design point, although not reaching NZEB status, represents an important step towards energy sustainability. In contrast, the NZEB point indicates that the building has not only minimized its consumption, but also managed to achieve a perfect balance between supply and demand by generating energy from renewable sources such as solar, wind or biomass.

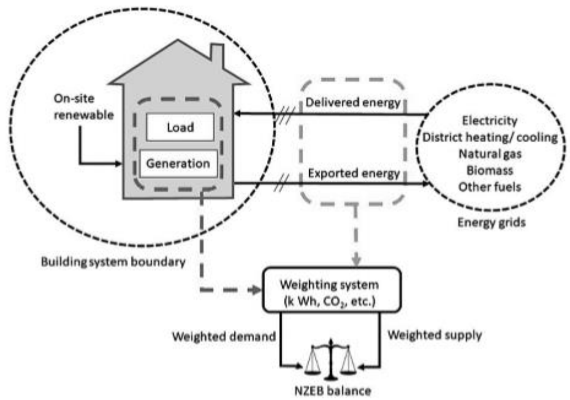



**Fig. 2.** System structure and essential elements of NZEB [5]

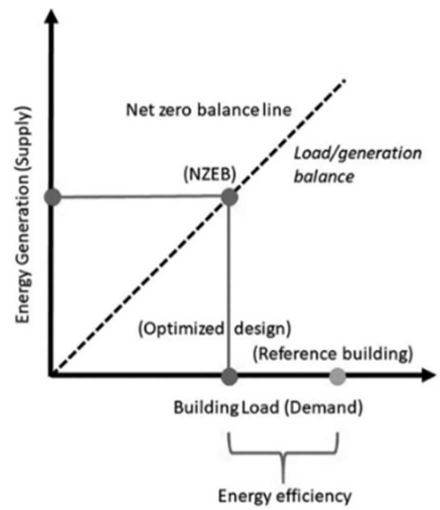



**Fig. 3.** The Graphic expression of NZEB [4]

Sartori et al.(2012) [4] proposed a simplified approach to describe NZEB, in which they showed that according to this approach, when the building boundaries are fixed, the balance of energy output and input during a given period should be greater than or equal to zero.

First of all, an NZEB must be a high-energy conservation performance building. In Figure 2, the baseline value of the weighted demand on the X-axis is the reference building value, which reflects basic energy conservation needs under local law. Here the possible reference building value refers to a representative value for a building of the same type and is used to make comparisons with the optimized design value. The higher the difference between the standard reference building value and the optimized design value, the higher the building's energy efficiency, which is equivalent to the concept of energy conservation performance in the NZEB framework. What is suitable energy efficiency? It will also be necessary to use high-performance energy conservation facilities and equipment to meet residents' need for comfort. At the center of the diagram in Figure 4 is the "Net Zero Energy Building." This is the ultimate goal where the total energy consumed by a building over a year is equal to the total energy produced from renewable sources on site (or building grounds).

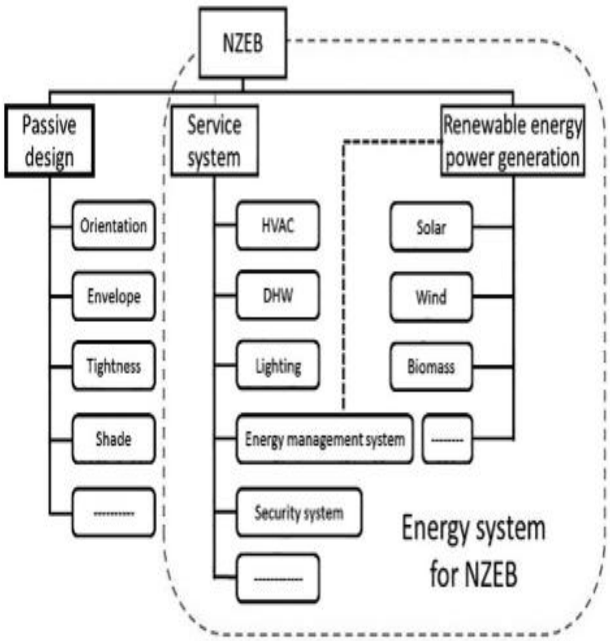



**Fig. 4.** Design elements for NZEB [5]

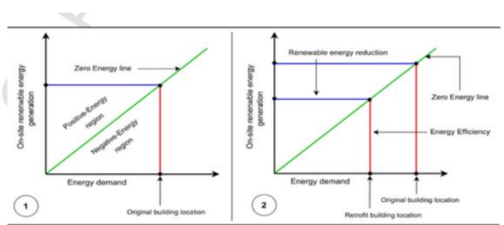



**Fig. 5.** The concept of achieving NZEB: (1) concept definition and (2) interrelation between energy efficiency and renewable energy generation [4]

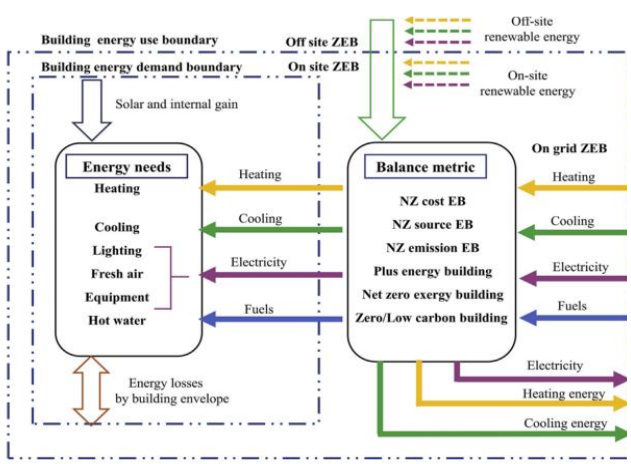



**Fig. 6.** Boundary specifications of applicable concepts [8]

Layer 1: Passive Design Strategies

This layer forms the foundation of a building's energy efficiency. These strategies take advantage of the natural conditions of the site and climate to minimize the building's energy needs without the use of complex mechanical systems. The elements of this layer are:

Envelope: This is the most important factor in reducing heating and cooling loads. This includes high-quality insulation, double or triple-glazed windows, and eliminating thermal bridges.

Domestic Hot Water (DHW): Although this is a service, this layer includes passive or highly efficient strategies for providing it (such as solar water heaters).

Shade: Design of shading devices (such as awnings, window eaves depth) to control solar radiation in different seasons and reduce cooling loads in summer, while allowing solar heat gain in winter.

Orientation: Optimal positioning of the building relative to the sun and prevailing winds to maximize solar gain in winter and provide natural ventilation in temperate seasons.

Lighting: Emphasis on daylighting design that minimizes the need for artificial lighting during the day through the use of windows, skylights, and light shelves.

Tightness: Creating a completely airtight shell to prevent unwanted air infiltration and exchange, which is a key principle in passive house building standards.

Layer 2: Service Systems

After minimizing energy requirements through passive design, this layer addresses the mechanical and electrical systems that are essential to meet the remaining building needs. The superior efficiency of these systems is critical.

Energy Management System: The brains of the building. This system prevents energy waste by continuously monitoring and optimizing energy consumption across all areas (including HVAC, lighting, and electrical outlets).

Air Conditioning (HVAC): This system should be highly efficient (such as high-efficiency heat pumps) and appropriately scaled (not larger than needed). The use of Heat Recovery Ventilation (HRV) systems for air conditioning with energy recovery is a key technology in NZEBs.

Layer 3: Renewable Energy Power Generation

This layer is the final step in achieving energy balance. After reducing the energy load (passive layer) and using efficient systems (active layer), the energy needed is now supplied from clean and renewable sources.

Renewable Energy Power Generation: This concept is generally realized with photovoltaic (PV) panels on the roof or on the premises of the building, which generate the electricity needed by the building.

Biomass: This source can be used to produce heat (for example, using wood or pellet boilers) as an alternative to fossil fuels.

Figure 5 analyzes the process of achieving net zero energy buildings (NZEB) from the perspective of energy demand and on-site renewable generation with two graphs. In the first graph, the original building is in the negative energy zone, meaning its consumption is greater than its renewable generation; while the green energy balance line represents the theoretical boundary between equal consumption and generation. The second graph, introducing the renovated building, shows the reduction of energy demand through optimization, which leads to a reduction in the need for renewable generation. This simultaneous reduction in consumption and generation is an effective path to achieving NZEB. The most important point is that optimizing energy consumption not only increases efficiency, but also reduces the cost and complexity of renewable generation systems.

## 5. Methodology

According to Figure 7, the database used is Web of Science (WOS), and the search was performed in the fields of titles, abstracts, and keywords. The time frame is five years, from 2020 to 2025, and the sources include journal articles and conference proceedings in English.

The data extraction date is recorded as 23 November 2025. In the initial stage, 667 records were identified. After removing irrelevant items (duplicates and out of scope records), 135 records were removed, and finally 532 records were included for the final bibliometric analysis.

To analyze the scientific structure of the field, VOSviewer software was used at three levels:

1-Keyword co-occurrence analysis – to identify hot thematic clusters.

2-Journal co citation analysis – to map influential journals.

3-Document co citation and clustering analysis – to discover dominant intellectual paradigms.

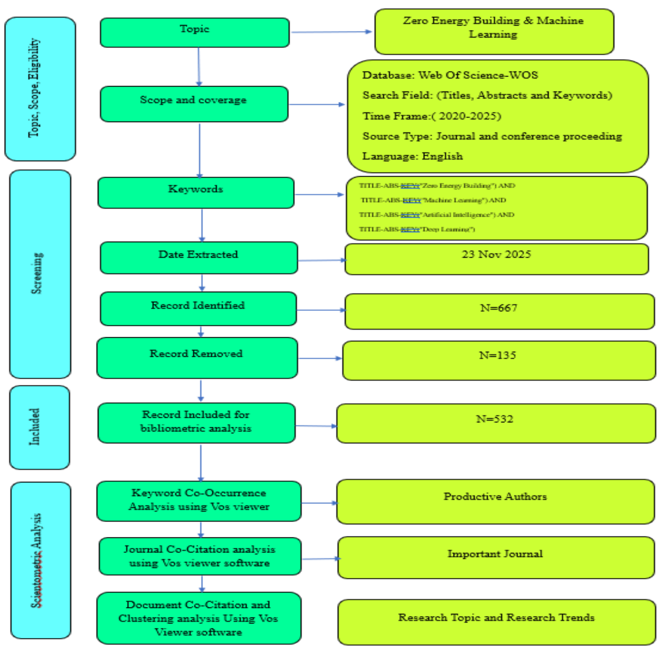



Figure 7 – Methodological framework of the bibliometric study: research trends in the field of Zero Energy Buildings and Machine Learning (2020–2025)

In selecting the study period, we opted for a short-term rather than a long-term analysis. The time frame of this study was set to five years, from 2020 to 2025, for several reasons. The most important reason is the growing and emerging trend of machine learning, deep learning, and artificial intelligence in zero-energy buildings, which has increasingly and significantly developed over these five years. This trend is not slowing down; rather, it continues with a steeper trajectory. This surge has coincided with the maturation of machine learning and AI algorithm applications, as well as the widespread availability of data from IoT sensors in buildings. Furthermore, this five-year period covers both the COVID-19 pandemic and the post-pandemic era. Although the pandemic itself is not directly analyzed in this study, it has indirectly influenced attention toward energy efficiency in buildings. In the initial round, approximately 532 articles published between 2020 and 2025 were reviewed based on keyword searches.

## 6. Results

We list journals and conferences that published more than 5 articles from 2020 to 2025 on this topic. These journals include Elsevier, Springer, Wiley, and IEEE. Table 1 shows the active scientific resources in the fields related to energy, buildings and artificial intelligence. Journals such as Applied Energy and Energy and Buildings with high citation counts (30 and 38) indicate the credibility and focus of researchers on them. The presence of conference series such as Lecture Notes in Computer Science and IOP Conference Series indicates that publication in conferences also plays an important role. The diversity of resources from specialized energy journals to interdisciplinary resources such as IEEE Access indicates the breadth of research topics.

**Table 1.** Journals and conferences that publish these topics

| Number | Source title |
|---|---|
| 15 | Energy Proceedings |
| 17 | Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) |
| 38 | Energy and Buildings |
| 30 | Energies |
| 23 | Journal of Building Engineering |
| 5 | IOP Conference Series: Earth and Environmental Science |
| 10 | Applied Sciences (Switzerland) |
| 5 | Renewable Energy |
| 20 | Buildings |
| 8 | IEEE Access |
| 7 | Sustainable Cities and Society |
| 6 | Renewable and Sustainable Energy Reviews |
| 9 | Sustainability (Switzerland) |
| 30 | Applied Energy |
| 9 | Building and Environment |
| 8 | Energy and AI |
| 5 | ASHRAE Transactions |
| 16 | Energy |
| 6 | Energy Reports |
| 10 | Lecture Notes in Networks and Systems |
| 6 | Sustainable Energy Technologies and Assessments |
| 12 | Lecture Notes in Civil Engineering |

**Table 2.** Frequently used keywords in this field

| Number | Keywords | No |
|---|---|---|
| 109 | Machine Learning | 1 |
| 76 | Artificial intelligence | 2 |
| 73 | Deep Learning | 3 |
| 54 | Energy Management system | 4 |
| 49 | Building Energy | 5 |
| 48 | Net Zero Energy Building | 6 |
| 44 | Renewable Energy | 7 |
| 39 | Energy Efficiency | 8 |
| 33 | Artificial Neural Network | 9 |
| 28 | Internet Of Things | 10 |
| 27 | Optimization | 11 |
| 26 | Forecasting | 12 |
| 25 | Solar Energy | 13 |
| 24 | Smart Grid | 14 |
| 23 | HVAC | 15 |

Table 2 shows the focus of recent research on integrating AI with energy management and sustainable buildings. Keywords such as Machine Learning, Artificial Intelligence, and Deep Learning are the most frequently used, indicating the central role of learning algorithms in optimizing energy consumption. Applied concepts such as Energy Management System, Net Zero Energy Building, and HVAC indicate that the ultimate goal is to improve efficiency and reduce consumption in building infrastructure. The presence of the Internet of Things and

Smart Grid also emphasizes the importance of connectivity and smartening networks. This distribution of keywords can be an effective guide for selecting future research topics in the field of energy and buildings.

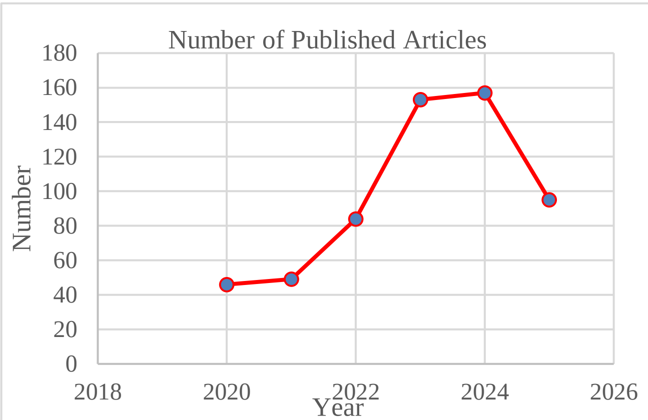
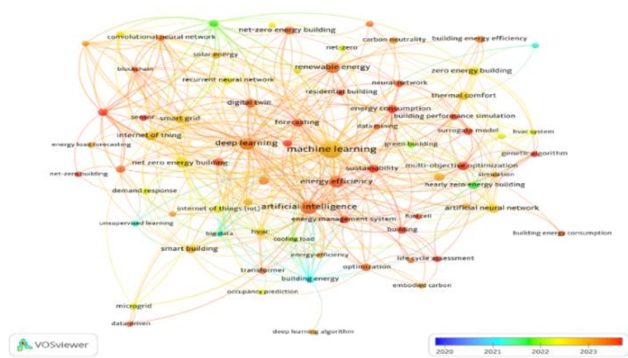



**Fig. 8.** Trend in the number of published articles (2020-2025)



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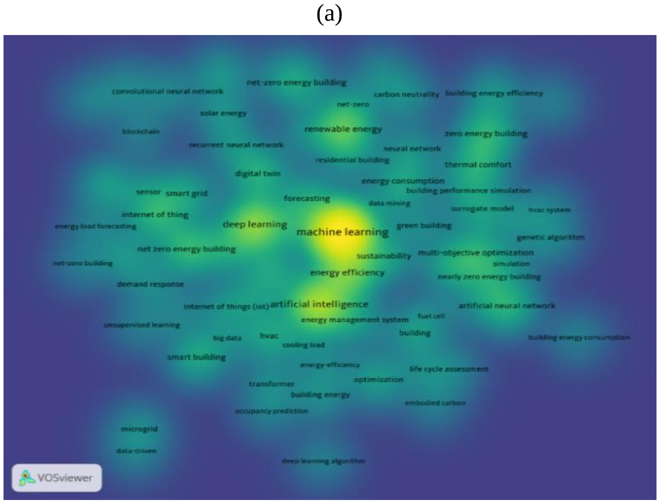
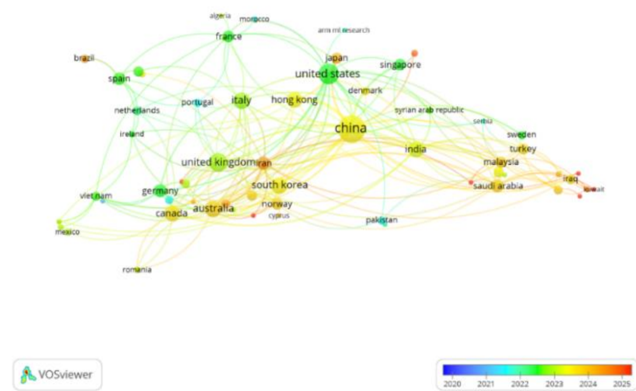


(b)

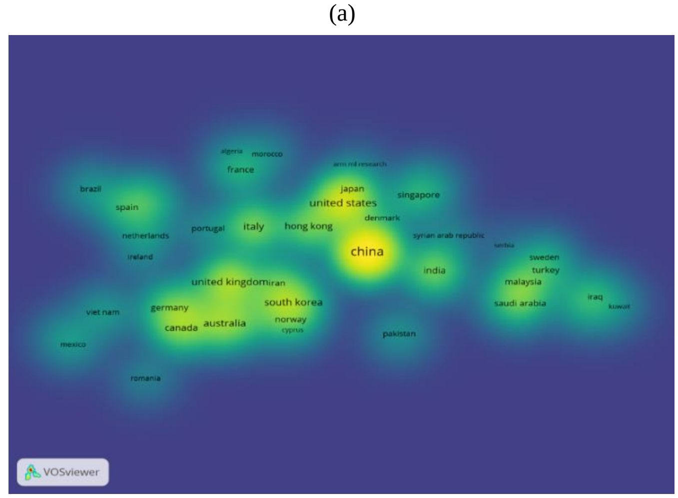
**Fig. 9.** Analysis of the structure of emerging research in the field of zero-energy buildings and artificial intelligence: a visualization of the co-occurrence of keywords and concept density using VOS viewer

Figure 8 shows the trend in the number of published articles from 2020 to 2025 (forecast). The number of articles started out with a fairly steady trend starting in 2020, but from around 2023 we see explosive and exponential growth. This rapid increase indicates the increasing focus and importance of the subject of study in the scientific community.

In Figure 9, section (a), the thematic focus in 2021 is shown to center around building energy and big data. At the beginning of 2022, attention shifted toward green buildings and nearly zero energy buildings. By mid-2022, the emphasis moved to topics such as HVAC systems, thermal comfort, solar energy, cooling load, and demand response, with IoT emerging as a key area of interest. The role of smart grids also became more prominent during this period. From early 2023 onward, machine learning and deep learning gained increased visibility, reflecting the growing importance of predictive algorithms. Environmental topics such as life cycle assessment also attracted attention, while economically driven themes like digital twins became more active and prominent, indicating a concentrated interest among authors in these areas. Figure 9, section (b), further illustrates the convergence of machine learning, deep learning, and artificial intelligence with themes such as net zero energy buildings, nearly zero energy buildings, and renewable energy. This intersection highlights the integrated significance of these three domains.



(a)

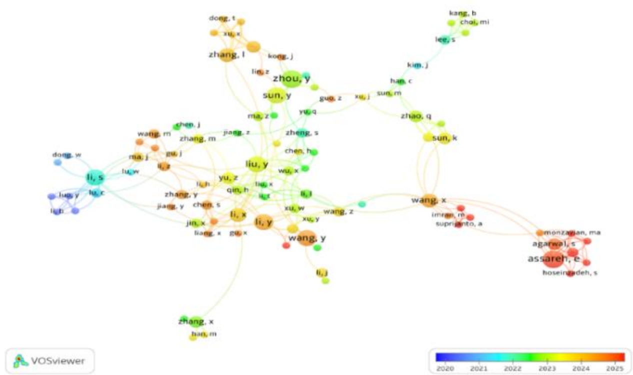


(b)

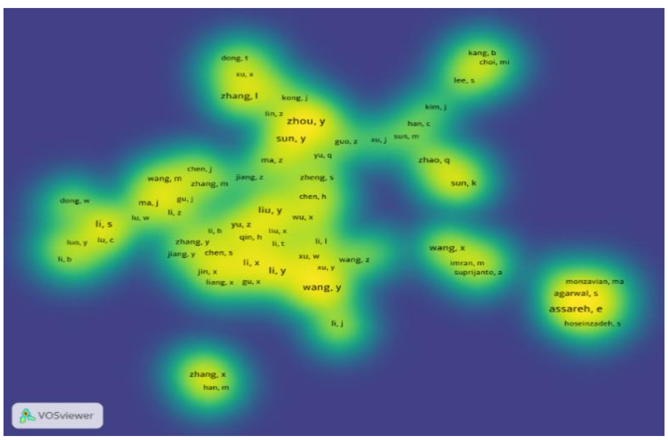
**Fig. 10.** Analysis of the structure of emerging research in the field of zero-energy buildings and artificial intelligence: a picture of the co-occurrence of countries and the density of concepts using VOSviewer

According to Figure 10, section (a), countries such as the Netherlands, Portugal, Serbia, Morocco, Pakistan, and Mexico made notable research contributions in 2021. In 2022, the focus shifted toward several European countries including Spain, Italy, Germany, Ireland, the Netherlands, and Sweden as well as leading nations such as the United States. From Asia, Vietnam and Singapore also demonstrated increased engagement with the topic. In 2023, Asian countries took the lead, with China, India, Malaysia, South Korea, and Australia showing significant activity. Among European countries, Norway exhibited a strong focus during this period. In 2024, Iran, Japan, and Saudi Arabia emerged as key contributors, followed by Iraq and Kuwait in 2025, which joined the group of leading and active research nations in this field.

Figure 10, section (b), clearly illustrates that the countries with the highest sustained focus on this topic include China, South Korea, Japan, and Iran from Asia; the United States and Canada from the Americas; and the United Kingdom, Germany, Spain, and Italy from Europe positioning them as global leaders in this area of research.




(a)




(b)

**Fig. 11.** Analysis of the structure of emerging research in the field of zero-energy buildings and artificial intelligence: a visualization of author co-occurrence and concept density using VOSviewer

According to Figure 11, several authors contributed to this field across different years. In 2020, researchers such as Dong, W., Luo, Y., and Li, B. published studies in this domain. In 2021, the most active contributors included Li, S., Lu, C., Lee, S., Kim, J., and Zheng, S. During 2022, Zhou, Y. and Zhao, Q. were among the leading authors in terms of publication volume. In 2023, notable contributions came from Li, L., Yu, Q., and Li, T. The year 2024 saw significant publications by Chen, S., Li, Y., and Wang, Y. Finally, in 2025, Assareh and Agarwal emerged as the most prolific authors in this area.

## 7. Discussion

### 7.1. Policy instruments for NZEB development across different regions

In the European Union, the Energy Performance of Buildings Directive (EPBD) has been the primary driver, mandating that all new buildings be nearly zero-energy by 2021 (public buildings by 2019). Member states have implemented diverse policy mixes, including minimum energy performance requirements, energy performance certificates, financial incentives (e.g., reduced VAT for energy-efficient materials, grants for renovation), and technical support programs. In the United States, there is no federal mandate for NZEB; instead, policies are implemented at state and local levels. Key instruments include building energy codes (e.g., IECC, ASHRAE 90.1), tax credits (e.g., Investment Tax Credit for solar PV), utility rebate programs, and voluntary certification systems (e.g., LEED, Zero Energy Ready Home). In developing economies located in hot and humid climates (e.g., parts of Southeast Asia, the Middle East, and Latin America), policy frameworks for NZEB are generally nascent. The primary barriers high upfront costs and long payback periods—are often exacerbated by subsidized energy tariffs that reduce the financial return on energy efficiency investments.

In summary, while the EU offers the most integrated regulatory-financial framework and the United States relies on a decentralized incentive-based model, developing economies in hot and humid climates face a distinct policy gap. For decision-makers, the evidence suggests that effective NZEB policies must be climate specific, incorporate cost effectiveness as a core criterion, and combine mandatory codes with financial mechanisms that address the initial cost barrier.

### 7.2. Barriers to NZEB development in hot and humid climates

The barriers hindering NZEB development in hot and humid climates can be systematically categorized into three interconnected groups: technical, economic, and regulatory challenges.

Technical challenges include high cooling and dehumidification loads throughout most of the year, which increase the required capacity of on-site renewable generation. Another challenge is the reduced effectiveness of conventional passive strategies, such as night cooling, due to the small diurnal temperature fluctuations. Furthermore, there is a risk of overheating in fully insulated buildings if natural ventilation is not properly managed. On the other hand, the performance of photovoltaic panels decreases under high temperature and humidity conditions, directly affecting the energy balance.

Economic challenges mainly involve high upfront investments for durable, mold- and mildew-resistant materials, as well as for efficient cooling equipment such as high-COP heat pumps or desiccant cooling systems, which are associated with long payback periods. This is particularly prohibitive in developing regions where energy tariffs may be subsidized and low.

Regulatory challenges include the absence of building energy codes tailored to tropical and subtropical climates, as most existing codes originate from temperate or cold climate frameworks, as well as the lack of standardized testing procedures for NZEB technologies under high-temperature and high-humidity conditions. In addition, financing mechanisms and tax incentives are often designed for energy efficiency measures that are more relevant to heating-dominated climates (e.g., insulation thickness) rather than cooling-dominated climates (e.g., cool reflective coatings or high-performance low-SHGC glazing).

These challenges directly inform design and optimization strategies. In response to technical challenges, the primary design response is a hierarchy of passive measures: (1) external shading with overhangs and adjustable louvers; (2) cool and reflective roofs and walls to minimize solar absorption; (3) optimized natural ventilation pathways using wind catchers or solar chimneys where possible; and (4) high-performance glazing with low SHGC. Once passive measures are exhausted, active systems must be properly sized using simulation-based optimization.

In response to economic challenges, cost-effective strategies prioritize measures with the shortest simple payback periods: cool roofs and wall coatings typically have a payback of less than 3 years; roof insulation, 5–7 years; and high-efficiency ceiling fans that allow a higher thermostat setpoint provide indirect payback through reduced air conditioner runtime. Renewable energy should be introduced incrementally starting with solar water heaters, followed by photovoltaic systems with net metering rather than attempting to achieve full on-site supply all at once.

### 7.3. Evaluation of artificial intelligence and machine learning applications in NZEB research

1. Energy load forecasting

Accurate forecasting of building energy demand (heating, cooling, electricity) is essential for achieving net-zero balance, as it enables proactive management of on-site renewable energy generation and storage. Common approaches include:

Short-term forecasting (hourly to daily) using Recurrent Neural Networks (RNNs), Long Short-Term Memory (LSTM) networks, and gradient boosting models such as XGBoost and LightGBM to predict heating and cooling loads based on weather forecasts, occupancy schedules, and historical data.

Uncertainty quantification via Bayesian neural networks or ensemble methods, which is particularly critical for NZEBs in hot and humid climates where sudden weather changes can destabilize the energy balance.

2. Predictive control and real-time optimization

AI and machine learning enable a shift from rule-based or reactive control to predictive control strategies. Key applications include:

Machine learning enhanced Model Predictive Control (MPC), where ML models act as surrogate models of thermal dynamics, reducing computational complexity and enabling real-time optimization.

Demand response integration, where ML classifiers predict real-time grid carbon intensity or electricity prices, allowing NZEBs to shift loads (e.g., EV charging, battery discharging) to periods of high renewable generation or low prices.

### 7.4. Limitations and challenges of AI and machine learning in the NZEB context

Data availability and quality are considered major limitations. Most machine learning models require large, high-resolution datasets (e.g., energy consumption at one-minute intervals, occupancy, weather conditions) for training. Such data are rarely available for existing buildings, especially in developing regions.

Generalizability across climates and building types is another important limitation. An ML model trained on office building data in a temperate climate performs poorly when applied to a residential building in a hot and humid climate due to different thermal dynamics and occupant behavior. The current literature consists mostly of single case studies; cross validation across multiple climates is rare.

Low interpretability and the trust issue are significant concerns. Deep neural networks and random forests, with hundreds of internal parameters, typically act as black boxes. If an intelligent control system suddenly raises the setpoint from 24°C to 27°C (to reduce load in response to a grid signal), the building operator without understanding the rationale may revert to manual control. Lack of transparency slows adoption. In NZEBs, operational permits require documentation of decision-making logic. Explainable AI (XAI) methods such as SHAP and LIME have rarely been used in this domain.

Absence of standard metrics and common benchmarks is another limitation. Researchers use different simulation software (EnergyPlus, TRNSYS, IDA ICE), different weather files (EPW, TMY), different occupancy profiles, and different error metrics (MAE, RMSE, MAPE, CV-RMSE). There is no common reference dataset akin to ImageNet in computer vision. This diversity makes quantitative comparison between different AI/ML methods impossible or at least very difficult.

## 8. Conclusions

This review paper provides a systematic analysis of the conceptual evolution, design frameworks, and global research landscape of Net Zero Energy Buildings (NZEBs) and nearly Zero Energy Buildings (nZEBs). The findings confirm that no universally accepted definition exists; rather, definitions vary depending on the region (European Union, United States) and project context. An empirically supported layered design hierarchy is identified: passive strategies (envelope, orientation, shading) reduce baseline loads; efficient active HVAC systems with heat recovery further reduce consumption; and finally, on-site renewable energy, primarily photovoltaics, offsets the remainder. The bibliometric analysis (VOSviewer) shows exponential growth in the number of articles from 2023 onward, with thematic shifts toward artificial intelligence, machine learning, deep learning, and digital twins. Key emerging keywords include energy management system, net zero energy building, HVAC system, smart grid, and Internet of Things. Geographically, research leadership has shifted from Europe and the United States (2021–2022) to Asian countries China, India, South Korea, Japan, Iran by 2023–2025. A persistent research gap has been identified: NZEB development in hot and humid climates, particularly in developing countries, remains severely underrepresented due to high upfront costs and long payback periods.

For industry practitioners and policymakers, the findings translate into actionable pathways. First, achieving NZEB in hot and humid regions requires a strategic emphasis on passive design (natural ventilation, adaptive thermal comfort models, shading) rather than costly active systems, because economic barriers dominate. Second, cost-effective strategies with short payback periods are essential; developing countries should prioritize technologies such as high-performance envelopes, daylighting, and solar water heaters over expensive storage or complex renewable systems. Third, policy and financial incentives are critical feed-in tariffs, tax credits, or low-interest loans can alleviate the upfront investment barrier. Fourth, integrating AI and machine learning into building energy management systems enables real-time optimization of HVAC and lighting, reducing operational costs and accelerating payback.

Based on the identified gaps and emerging trends, future research should pursue the following directions:

1. Climate specific NZEB solutions for hot and humid regions Develop and validate low-cost passive strategies, adaptive comfort models, and hybrid cooling systems tailored to tropical and subtropical climates, especially in developing economies.

2. AI based predictive control and digital twins – Investigate real time optimization frameworks that integrate IoT sensor data, weather forecasts, and occupancy patterns to minimize energy consumption while maintaining thermal comfort. The convergence of energy, AI, and digital twins observed in the bibliometric analysis requires deeper empirical validation.

3. Cost benefit analysis of NZEB technologies in underserved regions – Conduct life cycle assessments and payback period analyses for various passive and active technologies in hot and humid climates to develop evidence-based guidelines for policymakers.

4. Although the present bibliometric study qualitatively identifies high upfront costs and long payback periods as key barriers, a quantitative comparison of specific economic indicators (e.g., LCOE, payback period ranges, CAPEX/OPEX ratios) across different NZEB

technologies and climates was beyond the scope of this paper due to heterogeneous cost data reporting in the reviewed literature. Dedicated systematic reviews or original techno economic modeling are recommended to establish such benchmarks.

5.Occupant behavior and social acceptance – Given that adaptive comfort models depend on occupant interaction with natural ventilation, future research should incorporate the psychosocial factors affecting technology adoption and comfort expectations in tropical climates.

6. It should be noted that the trend of article publication across countries examined in the analysis of leading countries is based on raw article counts without normalization by the total national scientific output (e.g., total citable documents per country) or population. This constitutes a limitation of the present scientometric approach. Future studies could employ normalized indicators, such as the share of publications relative to the country's total scientific output in the energy or building field, or population-adjusted indices, to provide a more balanced picture of research productivity and the relative specialization of countries.

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## Appendix

Table I – Parametric comparative analysis of the research gap, innovations, strengths, and weaknesses of the present study relative to previous studies

| Type of study | Study period | Study area | Tools | Technological convergence | Addressing hot and humid climates | Using predictive approaches | Attention to developing countries | Providing policy advice | Research and Innovation Chat | Main limitations and weaknesses | Strengths | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research | ۲۰۲۰(Last 15 years) | Madagascar Island | Design Builder | LED light+ Air cooler chiller (CAV)+ battery storage+ Renewable Energy | √ | √ | √ | √ | Lack of research on Net Zero Energy neighborhoods on islands. Lack of decision-making tools and international standards for carbon accounting in tropical coastal areas | The proposed neighborhood design cost is 40-70% higher than existing neighborhoods in Madagascar, which is difficult to finance given the country's economic poverty. Focus only on residential buildings, not commercial ones. Model validation data was collected over a short period of time (not a full year). | First research of its kind in Madagascar and sub-Saharan Africa for sustainable neighborhood design. Combining several areas: thermal comfort, energy consumption, carbon emissions, cost and optimization. Providing a practical solution for the island of Madagascar, the third most vulnerable country in the world to climate change. | [54] |
| Research | Two years, including 2019 and 2020. | Utrecht province in The Netherlands | Experimental work and sensor use | Use of photovoltaic solar panels, air source heat pumps for heating and hot water production, digital sensors to monitor and control electricity consumption, solar generation, indoor temperature and thermostats, and reference to the potential for energy storage, demand response and reversible pumps for cooling. | × | × | × | √ | Lack of actual field studies of the performance of net-zero energy neighborhoods; most studies are simulation-based; Insufficient attention to the impact of occupant behavior on energy performance and thermal comfort in high-efficiency buildings | Lack of direct information from residents including number of people, household composition, behavior, changes in residence; Only one temperature sensor per house; Inability to perform multi-zone thermal modeling; Lack of objective measurement of thermal comfort based on advanced standards. Lack of easy generalizability to other regions with different cultures and climates | High-resolution 5-minute time-based data; full two-year period; 35 nearly identical homes (reducing design variables); simultaneous coverage of energy, production, occupant behavior, and thermal comfort; real-world evidence of neighborhood performance (not simulation); use of two NZEB definitions (site and emissions) and seasonal analysis | [55] |
| Comparative analysis-Review | ۲۰۲۲and2023 | Four projects in Norway and Sweden | Document analysis including comprehensive plans, reports, and energy certificates Analytical framework developed by the authors (including framework conditions, stakeholders, process, and outcomes) | Energy efficiency (e.g. insulation, heat recovery systems) Renewable energy generation (e.g. photovoltaics, geothermal heat pumps) Energy storage and flexibility (e.g. batteries, thermal storage) Energy efficiency (e.g. passive design, reduced floor space) | × | × | × | √ | Lack of research on the early stages of PED projects and how different stakeholders participate. Insufficient attention to the operational phase and monitoring of actual performance. Lack of research on the capabilities, roles and responsibilities of initiating stakeholders in participatory governance and citizen participation. Predominance of technological innovation over citizen participation. | The main limitation of the paper is that the design and performance of PEDs are highly context-dependent and direct replication of designs is not possible. Comparison of cases is also challenging due to the use of different software, metrics, and primary energy factors. Lack of adequate measures for energy resilience and adequacy at the neighborhood scale. Lack of legal consequences for developers who do not meet energy requirements. Weakness in monitoring and tracking energy performance after operation. | Initial focus on energy goals in the planning stages. Master plan as a key tool for aligning interests. Simultaneous attention to building and neighborhood balance to reduce environmental impacts. | [56] |

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| Case Study | 2025 | The University of Palermo campus in southern Italy | Energy Plus+ SketchUp + Sima Pro | Building shell optimization (rock wool and cork insulation). Low-emission windows with aluminum frames with thermal breaks. LED lighting systems. Replacement of HVAC system with electric reversible heat pumps. Photovoltaic panels on the roof. | × | to some extent | × | √ | Most PED studies have focused on low-density suburban-residential areas. Lack of studies in high-density, energy-intensive non-residential areas (such as university campuses). Lack of integration of life cycle assessment (LCA) with PED objectives. Need for studies in Mediterranean climates with tall buildings and spatial constraints for on-site renewable energy generation. | Very difficult to achieve a mathematical positive energy balance in areas with high building density. The current definition of PED is not flexible enough for different situations. Failure to consider economic costs and social aspects in the assessment. Failure to fully achieve the PED goal (negative final balance). Transfer of environmental impacts from the operation phase to the construction phase (embodied impacts). Failure to examine the replicability in other similar areas. | Holistic and integrated approach (energy simulation + LCA + PED framework). Performing sensitivity analysis for the useful life of materials. Innovation in PED assessment for a high-density Mediterranean non-residential area. | [57] |
| Developmental-applied and methodology | 2024 | - | adoption score-based decision-making | Hybrid systems such as PV/T (photovoltaic/thermal) and PV + heat pump have been investigated. | × | × | × | × | Lack of a comprehensive framework for simultaneously integrating active and passive solar strategies into urban planning. Lack of decision-making tools that incorporate solar analysis results into early stages of urban planning. Research focuses more on PV (photovoltaics) rather than a holistic approach. | The survey was conducted only among IEA Task 63 experts and requires the participation of other professions (architects, engineers, planners, developers). The variability of technologies and regulations requires continuous updating of data and prioritization. | Simultaneous integration of active and passive solar strategies in new and existing neighborhoods. Comprehensive multi-criteria approach including technical, economic, environmental criteria. High flexibility to adapt to different climates and regions and add new technologies. Sensitivity analysis to examine the impact of different criteria weights. | [58] |
| Bibliometric analysis | ۲۰۲۰-2025 | World | VOS viewer | Convergence of zero-energy concepts with artificial intelligence, machine learning, learning | √ | √ (It has been used in a systematic review of articles.) | √ | √ | There is a severe lack of studies on the development of zero-energy neighborhoods in hot and humid climates, especially in developing countries. | Failure to normalize article counts based on total national scientific production or country populations (in the analysis of leading countries). | Covering the short and emerging time frame (2020-2025) coinciding with the peak of ML/AI application development. Scientific structure mapping including keyword co-occurrence, co-citation and concept density analysis with VOSviewer. Identifying the geographical shift of research leadership from Europe/America to Asia. | This Study |