

Design Strategies, Technologies and Automation for Achieving Net-Zero Energy Consumption in Civil Buildings

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Abstract

The increasing demand for energy-efficient infrastructure and the global urgency to mitigate climate change have accelerated the adoption of Net-Zero Energy Buildings (NZEBs) in the civil building sector. This paper explores the interplay between design strategies, technological and automaton innovations aimed at achieving net-zero energy performance in civil buildings, such as schools, hospitals, government facilities, and community centers. It emphasizes a two-tiered approach: prioritizing passive design strategies like site orientation, thermal mass utilization, natural ventilation, and daylighting, before deploying active technologies like solar photovoltaic systems, high-efficiency HVAC, Building Management Systems (BMS), and energy storage solutions. Key challenges deterring the full realization of NZEBs include high initial costs, lack of technical expertise, inadequate policy frameworks, and inconsistent user behavior. To address these issues, the paper recommends integrated design thinking, capacity development, climate-responsive planning, policy and software engineering support through performance-based building codes and financial incentives. By showcasing global best practices and referencing successful case studies, the paper concludes that achieving net-zero in civil buildings is both feasible and imperative.

Keywords: *Energy Grid, Peak Demand Period, Reduced Operational Costs, GHG Emission, Peak Load Management, Software Engineering, Smart Building Technologies, Energy Simulation, Python Programming, Internet of Things (IoT).*

I. INTRODUCTION

Civil buildings are buildings primarily designed for public use or private civilian occupancy and external usage, which excludes industrial, military, or highly specialized technical facilities. Civil buildings are important forms of core urban and community infrastructure, intercepting a vital role in social, historical or preservation administrative, educational, cultural, or residential functions. (Olotuah, & Aiyetan, 2006). Examples of civil buildings include residential buildings, healthcare facilities educational institutions, government buildings, commercial structures, relaxation and recreational centers. In architectural discourse, civil buildings adhere to civil engineering and architectural design principles focused on human comfort, ease way finding designs, safety, and sustainability. Before being subjected to broader design implementations such as energy efficiency, environmental impact, urban integration, and public interaction and usability. (Geiger, Gade, Von Scheven, & Bischoff, 2020).

Net-Zero Energy Buildings (NZEBs) are innovative solutions in architecture and civil engineering that aim to produce as much energy by these construction products as they consume energy over a year. An NZEB is a building connected to the energy grids having the ability to satisfy its yearly energy balance and as such, capable to match its own energy load or

consumption with on-site energy generation and work beneficially with the local grid expectations or needs. (Sartori, Napolitano, & Voss, 2012). This means that these buildings uses a combination of on-site renewable energy generation and energy efficiency strategies to reduce energy demand and optimize environmental performance. (Lou, & Hsieh, 2024). Greenhouse gas (GHG) emissions, which primarily is carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), significantly contribute to global warming and climate change. These gases trap heat in the atmosphere, leading to rising temperatures and impacts on ecosystems, human health, and economies. Sources of greenhouse gas emissions could include land use changes,

agriculture, fossil fuel combustion, and industrial processes like cement production, groundbreaking or drilling and steel manufacturing. (Zien, M., & Kirschstein, 2023). The impacts of greenhouse gas emissions are numerous in the ecosystem ranging from climate change, air pollution, and water scarcity. And according to Ugonabo, & Oladejo, (2023). The mitigation strategies include transitioning to renewable energy sources, improving energy efficiency in buildings, transportation, and industry, implementing sustainable land use practices, and developing and deploying carbon capture and storage technologies. Understanding the sources, impacts, and mitigation strategies of GHG emission is vital for developing effective policies and solutions to address this research topic. Transitioning to renewable energy sources, improving energy efficiency in buildings, even transportation, and industry, implementing sustainable land use, and developing and deploying carbon capture and storage technologies are all effective ways to mitigate greenhouse gas emissions.

This paper explores the core design strategies, technological innovations, and implementation challenges involved in achieving net-zero energy consumption in civil buildings, aiming to provide a comprehensive understanding of NZEBs and their role in sustainable urban development.

II. NET ZERO ENERGY BUILDINGS

The concept of Net-Zero Energy Building (NZEB) is a sustainable energy system that aims to achieve a net energy balance of zero or even positive, provided that the building's operational boundaries remain constant. (Wells, Rismanchi, & Aye. 2018). The global commitment to achieve carbon neutrality has become a priority, with major economies like the European Union and the United States pledging to achieve it by 2050 (Williams, Lomas, Abohela,

2021). These commitments are part of broader sustainability efforts aimed at reducing greenhouse gas emissions, decreasing reliance on fossil fuels, and addressing increasing energy demand through more efficient and cleaner technologies. Net-Zero Energy Buildings (NZEBs) are central to these strategies, designed to produce as much energy as they consume over a specified period, ideally for a year. However, regulatory frameworks and policies are evolving to support the adoption of NZEBs, but significant discrepancies remain in the definitions and calculation methodologies employed across international bodies. This inconsistency has led to confusion within the global building and energy sectors, with over 70 different NZEB definitions currently in use worldwide. Achieving net-zero goals requires not only technological innovation but also clear, standardized definitions and frameworks to guide stakeholders, policymakers, and designers globally. (Harkouss, Fardoun, Biwole, 2018).

This concept is visually represented in Figure 1a and b below, which plots various weighted resources, such as CO₂ emissions and equivalent primary energy, on the vertical axis. NZEB status is achieved when the weighted energy production equals or exceeds the weighted energy consumption within a defined timeframe and within consistent system boundaries. The energy balance is typically analyzed using energy conversion calculations, where weighted supply and demand are plotted on the y-axis and x-axis, respectively. Renewable Energy sources contribute to the ordinate (y-axis), symbolizing the amount of electricity generated, while energy demand is depicted along the abscissa (x-axis). The performance of a model building can be assessed based on its energy balance over time. The NZEB designation is confirmed when the net difference between weighted supply and demand is equal to zero.

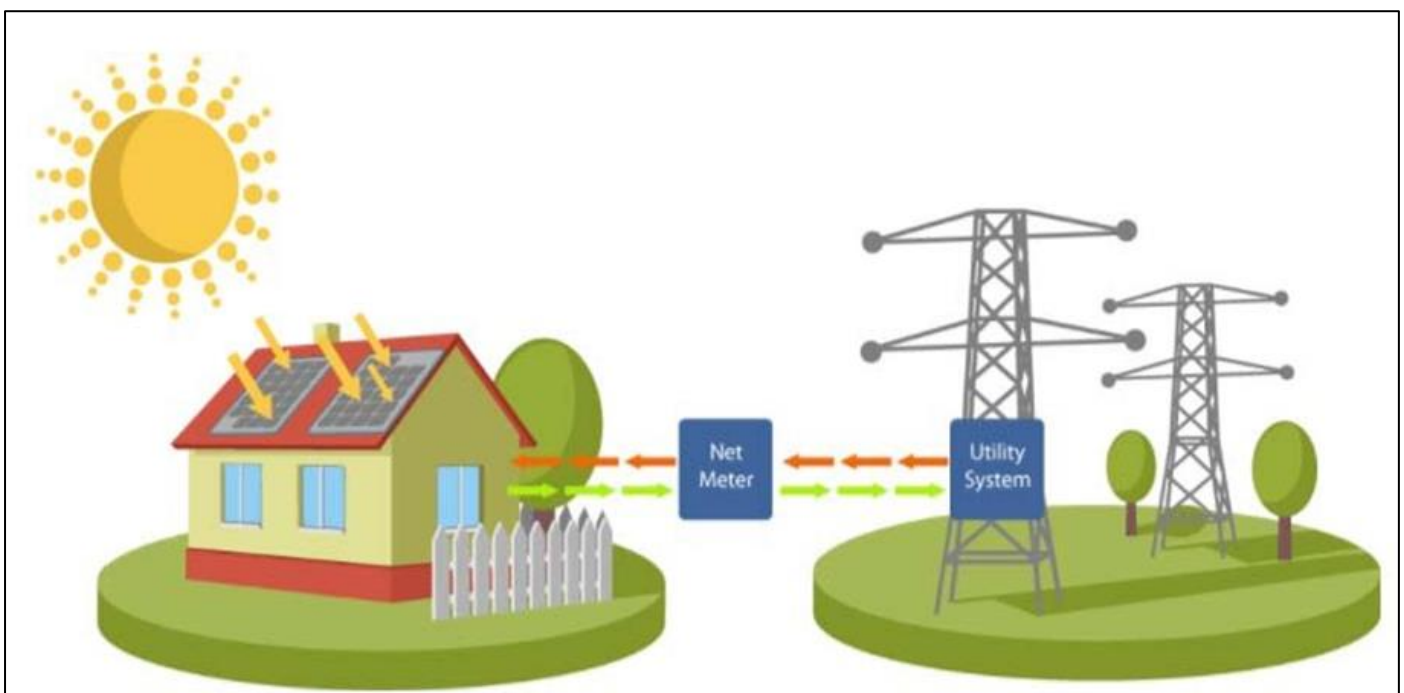


Fig 1(A) The Concept of Net-Zero Energy Building
Source: Google (2019)

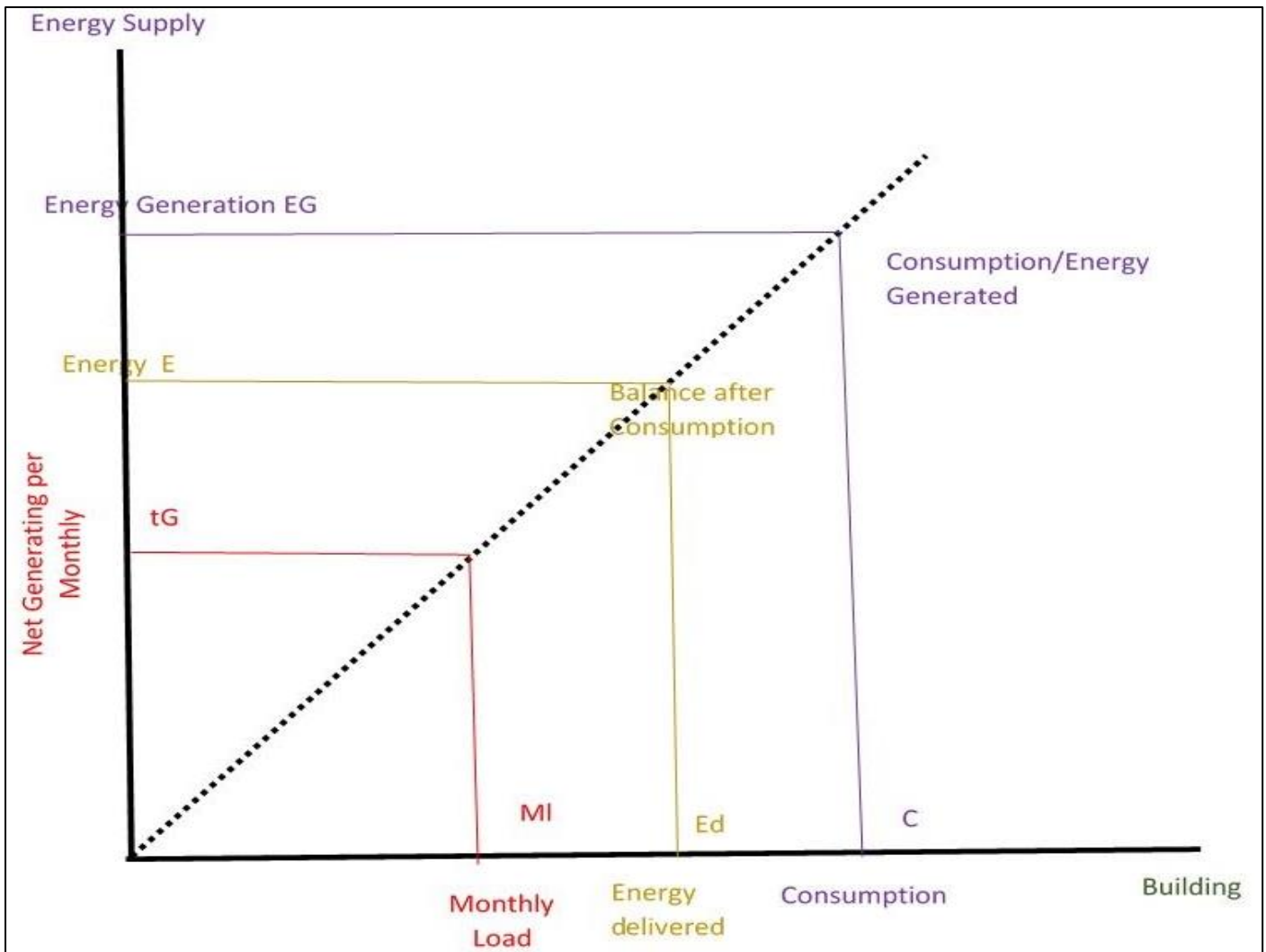


Fig 1(B) Schematic Diagram Showing the Concept of Net-Zero Energy Building
Source: Google (2019)

III. CLASSIFICATIONS OF NET-ZERO ENERGY BUILDINGS

The classification of Net-Zero Energy Buildings into site, source, cost, and emissions categories provides a structured framework for defining performance goals, comparing building projects, and aligning with regulatory or environmental targets. While each classification offers unique insights, they are not mutually exclusive and may be combined depending on the building design objectives, policy context, and stakeholder priorities. (Torcellini, Deru, & Crawley, 2006).

➤ *Net Zero Energy Site*

This classification in building produces at least as much energy as it consumes on-site over a year, focusing on local self-sufficiency and encouraging the integration of on-site renewable systems like solar PV and wind turbines. This approach is common in small to medium-scale projects with available space for renewables.

Net-Zero Energy Site Buildings are civil buildings with rooftop solar panels that generate electricity and energy-efficient appliances. They use photovoltaic systems, daylighting through windows, and natural ventilation to reduce air conditioning use. This system

produces as much energy as it uses annually without requiring extra grid energy.

➤ *Net Zero Energy Source*

This considers the total primary energy used to generate and deliver energy to the building, including transmission, conversion, and distribution losses. This classification provides a more comprehensive view of energy impacts, especially when comparing different energy sources.

Example of this is the Net-Zero Energy Source building, such as the University Research Lab Building in Germany, uses energy-efficient systems to minimize consumption. It buys electricity from certified green sources like wind farms or hydroelectric plants and has solar panels on the roof to generate additional power. The total primary energy consumed is equal to the primary energy generated or offset, considering energy losses in the system. Even if the solar panels are off-site, the building compensates for the energy it uses from a source perspective, making it a Net-Zero Source Energy building.

➤ *Net-Zero Energy Cost*

This is when building balances the monetary value of energy exported (e.g., to the grid) equals or exceeds the

value of energy imported over a year. This approach is particularly relevant in economic feasibility studies and return-on-investment analyses.

Example is the Net-Zero Energy Cost building in Lagos, Nigeria. A system where the money spent on energy equals the money saved or earned from energy generation over the year. The home uses solar panels on the roof, generates more electricity during the day than it uses, and sells the extra electricity back to the grid through a net-metering agreement with the local utility. At night, when solar is not available, the home uses grid electricity. At the end of the year, the cost of grid electricity used is approximate to the value of solar energy sold back to the grid, making the total net cost of energy for the homeowner zero.

➤ *Net-Zero Energy Emissions*

Building achieves a balance between carbon emissions associated with energy use and emissions avoided or offset through renewable generation or carbon credits. This classification aligns closely with climate action goals and carbon neutrality targets. Key features include measuring environmental impact in terms of CO₂ equivalent and encouraging the use of low- or zero-carbon energy sources.

Example is the modern office building in Nairobi, Kenya, uses 100% renewable energy, including solar and wind power, and energy-efficient lighting, HVAC, and low-carbon materials. For small emissions, such as construction equipment or backup diesel generators, the building purchases carbon offsets like tree planting programs and carbon credits from clean cookstove projects in rural areas. This type of net-zero focuses on greenhouse gas emissions, especially CO₂, and is often used for urban buildings that cannot generate all their energy on-site but still want to meet climate-friendly standards. The building's net carbon emissions are zero, even if it uses some non-renewable energy at times.

IV. DESIGN STRATEGIES OF NET ZERO ENERGY BUILDINGS

Net-zero energy building design applies some strategies to balance energy consumption with renewable energy production, thereby minimizing carbon footprint.

These includes;

➤ *Passive and Active Design Strategies*

Achieving net-zero energy consumption in civil buildings requires a balance between passive and active design strategies. (Elaouzy, & Fadar, 2022). Sustainable architecture best practices emphasize employing passive design strategies firstly before incorporating active design strategies, as this hierarchy aligns with energy efficiency principles, ensures cost-effectiveness, and long-term operational sustainability, while also enhancing environmental performance.

Passive Design Strategies are method of regulating indoor conditions and energy revolution of buildings

without relying on mechanical systems or external energy inputs. These strategies are based on climatic responsiveness and are considered the first line of defense in reducing a building's energy demand. (Ding, 2024). Key passive elements include building orientation, natural ventilation, microclimate conditioning, and thermal mass, shading devices, daylighting, insulation and airtight building walls. Understanding Passive Design Strategies further looks into Building orientation which is the placement of building on site optimizes sunlight exposure for natural lighting and thermal gain, especially in colder climates. Passive strategies are typically lower in cost, require less maintenance, and offer greater resilience, particularly in off-grid or resource-constrained environments.

Active Design Strategies involve the use of electrical, mechanical and renewable energy systems to meet remaining energy needs after passive design strategies had been maximized. (Elaouzy, et al., 2022). These systems are more efficient and effective when the civil building required energy load has already been reduced through passive design. These strategies involves the use of photovoltaic panels, high-efficiency HVAC systems, smart lighting and appliances, and energy management systems.

In the approach to optimize net-zero design, passive designs come firstly in design and approaches of functionality, rigidity and aesthetics, active secondly with active design principles to compliment prioritizing the longevity of the civil building before introducing more complex technological solutions.

➤ *Energy Efficiency of Building*

This approach is the vital in sustainable building design and net-zero energy strategies. It emphasizes the importance of minimizing a building energy demand through smart design and technological efficiency before incorporating renewable energy systems. In civil buildings, this approach is cost-effective and logical, as it reduces energy consumption as much as possible and supplies the reduced demand through clean, renewable sources.

It is almost similar to the first principle but stands out, (Oluwunmi, Ogunsemi, & Adejimi, 2019). Once a civil building energy load is minimized through efficiency measures, on-site renewable energy systems can be introduced to meet the reduced demand. This sequential approach ensures that renewables are right-sized, economically viable, and environmentally effective. This was buttressed by Ryghaug & Sørensen (2009), that this makes designing for energy efficiency address the root of energy consumption, ensuring more sustainability to eliminate waste and optimize performance than simply adding more solar panels or other renewable systems, reducing initial investment in renewable technologies but also enhances the building's long-term operational performance and resilience. Energy efficiency for reducing energy demand includes using high-performance building envelopes, passive design techniques, efficient lighting and appliances, optimized HVAC systems, and energy

modeling and simulation tools like EnergyPlus or DesignBuilder.

This principle is enshrined in green building certification systems like Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Nigeria Green Building Council guidelines, which encourage energy audits, efficiency benchmarking, and performance validation before approving renewable system integration. In the Nigerian context, prioritizing efficiency is particularly crucial, as the integration of passive cooling, improved insulation, and user education in public buildings could significantly reduce grid dependency and promote energy equity.

➤ *Life Cycle Thinking (LCT)*

This is a crucial strategy in sustainable architecture and engineering, focusing on the entire lifespan of a building, considering the entire process from material extraction and production to construction, use, maintenance, and eventual demolition or reuse. This holistic approach evaluates environmental impacts, resource consumption, and long-term costs across each stage of the building life, enabling more informed design decisions that contribute to sustainability, resilience, and circularity.

➤ *Energy Demand Management (EDM)*

This is a crucial strategy for achieving net-zero energy consumption in civil buildings. (Al Dakheel, Tabet Aoul, & Mourshed. 2020). It involves monitoring, controlling, and reducing energy use within a building, especially during peak demand periods.

Peak demand periods are times of day or season when energy usage is highest, putting maximum stress on the electrical grid. Examples include mornings and evenings in homes, middays in offices, and seasonal changes in hot and cold climates. Peak load management is crucial for achieving net-zero goals, as electricity often comes from less efficient and polluting sources during peak demand times.

EDM involves both behavioral and automated interventions that can dynamically adjust energy consumption based on occupancy, environmental conditions, and system efficiency. It not only improves the energy performance of buildings but also reduces stress on the grid and facilitates the integration of intermittent renewable energy sources.

Several technologies and operational approaches support EDM in civil buildings, including smart meters & sub-metering systems, automated lighting & HVAC controls, peak load shifting, and demand response programs. EDM acts as the first line of defense in the net-zero strategy, allowing buildings to install smaller, more cost-efficient energy generation systems. Studies show that load reduction through EDM contributes up to 30-40% of total energy savings required for NZEBs. (Torcellini, *et al.* 2006).

➤ *Application of Sustainable Design*

Sustainable design helps in reducing environmental impact in buildings by integrating renewable energy technologies, minimizing waste, and optimizing performance. (Friesen & McLeod, 2021). This approach considers the building usage now, providing for its energy consumption and it not affecting the building in the future. It was buttressed by Kibert, C. J. (2007), sustainable design is the practice of designing buildings, products, or systems with a focus on minimizing environmental impact while maximizing efficiency and functionality throughout their life cycle. It aims to reduce non-renewable resource consumption, waste, and pollution while promoting well-being for individuals and communities. Key principles include energy efficiency, resource efficiency, environmental impact reduction, health and comfort, and economic sustainability. Key takeaways include that sustainable design is not just about the environment but also concerns economic viability and social responsibility. Examples of sustainable design applied in the building industry include green buildings and Net-Zero Energy Buildings (NZEBs).

➤ *Cultural Consideration*

Behavioral architecture is a essential field of design that focuses on the interaction between human behavior and the built environment. It integrates insights from psychology, sociology, environmental design, and cognitive science to inform architectural decisions. (Aleyomi, & Nwagwu. 2020).

Cultural considerations are important in homes, schools, hospitals, and public spaces as such, behavioral design aims to create environments that promote comfort, efficiency, social interaction, and well-being.

Cultural considerations are crucial in designing buildings that aim to achieve net-zero energy consumption, particularly in tropical regions like Nigeria or other parts of Africa. These in civil buildings are built in specific cultural, climatic, and social environments, and when integrated into architectural design, can enhance energy efficiency, improve occupant comfort, and reduce reliance on mechanical systems. Traditional architectural practices often offer low-energy solutions adapted to local conditions, which modern sustainable design can draw upon to achieve NZEB performance.

Cultural design strategies that support net-zero energy goals include passive cooling from vernacular architecture, optimizing orientation and space use, using locally sourced, climate-responsive materials, incorporating behavioral patterns and occupancy, and integrating aesthetic and identity integration. (Olotuah, & Adesiji, 2005). Incorporating these culturally rooted strategies into modern civil buildings can significantly reduce energy loads and help achieve NZEB targets.

Incorporating culturally informed design with modern NZEB systems can enhance energy efficiency, social acceptance, and climatically appropriate buildings. By aligning Net-Zero Energy goals with traditional

knowledge, occupant behavior, and local material use, architects and planners can create civil buildings that are energy efficient, socially embraced, and climatically appropriate. (Olusanya, & Jimoh, 2017).

V. DESIGN TECHNOLOGIES OF NET ZERO ENERGY BUILDINGS

➤ *Energy-Efficient Heating, Ventilation, and Air Conditioning (HVAC) Technologies*

Energy-efficient HVAC technologies are crucial for achieving significant reductions in operational energy demand, enhancing indoor environmental quality, and supporting long-term sustainability goals in Net-Zero Energy Buildings (NZEBS). These technologies are designed to minimize energy input while maximizing thermal comfort, air quality, and system performance through innovations in equipment, control, and design integration. (Ogunmakinde, & Sher, 2021). There are several types of energy-efficient HVAC technologies, including,

- *Variable Refrigerant Flow (VRF) Systems*

Variable Refrigerant Flow (VRF) systems are advanced HVAC technologies that provide flexible, energy-efficient heating and cooling for various building types. Originating in Japan in the 1980s, VRF systems can serve multiple zones simultaneously while optimizing energy usage. They are particularly relevant in the context of Net-Zero Energy Buildings (NZEBS) and high-performance civil buildings, (Attia, & Carlucci, 2015). VRF systems use inverter-driven compressors to modulate refrigerant flow to match the exact cooling or heating demand of each zone. They offer energy efficiency, zonal control, space saving and flexibility, and reduced operational cost. However, high initial costs, installation complexity, and the need for specialized technicians may limit adoption, especially in developing countries. VRF systems align well with NZEB objectives by minimizing HVAC loads, reducing peak energy demand, and improving building energy performance ratings under frameworks like LEED and BREEAM.

VRF systems utilize renewable energy, particularly effective in sunny climates like Nigeria, and provide passive cooling, improved indoor air quality, and lower fan energy consumption.

- *Energy Recovery Ventilation (ERV) Systems*

This captures and transfers energy from exhausted air to pre-condition incoming fresh air, reducing the heating or cooling load required for ventilation air. This enhances indoor air quality (IAQ) and reduces HVAC energy by up to 60% in some climates. Solar-Assisted HVAC Systems can supplement or replace traditional mechanical heating and cooling sources.

According to U.S. Department of Energy. (2020), Energy Recovery Ventilation (ERV) systems are mechanical ventilation solutions designed to improve indoor air quality (IAQ) and conserve energy in buildings. They work by transferring heat and moisture between

incoming fresh air and outgoing exhaust air, reducing the load on heating and cooling systems. The importance of this includes improved IAQ, reduced HVAC energy use by up to 50%, moisture control, and better occupant health and comfort. ERVs support Net-Zero Energy Buildings (NZEBS) by reducing ventilation energy loads and enhancing the overall building envelope efficiency.

- *Ground Source Heat Pumps (GSHPs)*

Ground Source Heat Pumps (GSHPs), also known as geothermal heat pumps, are high-efficiency heating and cooling systems that use the stable temperature of the earth below the surface to regulate indoor climate. Unlike conventional HVAC systems, GSHPs exchange heat with the ground, which remains at a stable temperature year-round. GSHP systems work through a series of buried pipes filled with a heat transfer fluid that circulates through the earth. They can achieve 300-600% efficiency, low operating costs, reduced greenhouse gas emissions, and are quiet and durable, with few moving parts and low maintenance. (Lund, Freeston & Boyd, 2010)

They are ideal for Net-Zero Energy Buildings (NZEBS) as they significantly reduce heating and cooling loads, integrate well with renewable energy sources, and are effective in both residential and civil buildings. However, challenges include high initial installation costs, the need for sufficient land area or vertical boreholes, and the need to design the system to suit local geology and climate.

- *Hybrid Systems of Displacement Ventilation and Natural Ventilation*

Hybrid ventilation systems, which combine displacement ventilation (DV) and natural ventilation (NV), are an effective strategy for energy-efficient and net-zero energy buildings (NZEBS). These systems leverage both passive (natural airflow) and low-energy mechanical techniques, optimizing performance across varied climate conditions and occupancy patterns. Displacement ventilation is a low-velocity mechanical ventilation method that introduces cool, fresh air at floor level, allowing it to rise naturally as it is warmed by heat sources. It works with stratification, using the natural buoyancy of warm air and effectively enhances indoor air quality by removing pollutants and CO₂-laden air. (Zhao & Li, 2020).

Natural ventilation uses openings such as windows, vents, louvers, and architectural features to promote air exchange, driven by wind pressure and thermal buoyancy. It offers no mechanical energy required, is useful in transitional climates or mild seasons, and enhances occupant satisfaction and reduces operational costs. Hybrid systems are especially suitable for educational buildings, offices, healthcare centers, and public halls, as these spaces often require good air quality and comfort without the high energy use of conventional HVAC systems. Advantages for NZEBS include reduced HVAC energy consumption by up to 40%, improved indoor air stratification, enhanced thermal comfort, and daylighting integration. Challenges include careful architectural design, coordination with passive solar strategies, automated control systems, and

climate-dependent performance evaluation through building energy simulations.

- *Smart Grid Systems and Demand Response Technologies.*

Smart Grid Systems and Demand Response Technologies play a crucial role in aligning building energy consumption with grid conditions, enabling buildings like offices, schools, and public institutions to become intelligent energy consumers and producers. Smart Grid Systems use digital communication technologies, sensors, and automated control systems to manage electricity generation, distribution, and consumption more efficiently. Key features include two-way communication between utilities and consumers, real-time monitoring of energy flows, and integration of distributed energy resources (DERs) like solar PV and wind.

Demand Response (DR) refers to technologies and strategies that allow buildings to temporarily reduce or shift electricity use during peak demand periods or when the grid is under stress. It works by signaling high-demand events, adjusting loads, and incentivizing occupancy to reduce or shift energy use. DR types include manual DR (user-driven changes based on time-of-use) and automated DR as intelligent systems respond without human input. (Fang, Misra, Xue & Yang, 2012).

Benefits in civil buildings include peak demand reduction, lower energy bills and grid strain, enhanced grid integration, and improved building performance, support for smart HVAC and lighting automation, and support for energy storage. In developing countries like Nigeria, integrating smart grid-ready infrastructure supports microgrids and solar hybrid systems, enables smart load shedding, battery prioritization, and diesel generator reduction, and improves energy security and reduces reliance on backup fossil fuel systems.

➤ *Building Automation & Energy Management*

Building automation and energy management is the integration of technology and systems to monitor, control, and optimize the performance of a building. Focusing on energy consumption, indoor comfort, and operational efficiency. Automation technologies are crucial for achieving energy efficiency, cost savings, sustainability goals, and Net-Zero Energy Building (NZEB) performance. Modern systems are intelligent and equipped with machine learning capabilities. It employs the following medium.

- *Building Management Systems (BMS)*

This is a centralized system that optimizes the operation of mechanical, electrical, and electromechanical services in a building. It allows for centralized control of temperature, lighting, ventilation, scheduling, fault detection, security and energy usage optimization, contributing to energy savings and greenhouse gas emissions reduction. BMS is essential for net-zero energy buildings.

- *Smart Thermostats*

These are building automation technologies (e.g., Nest, Ecobee), designed for HVAC control at the room level, offering features like learning user behavior, using occupancy sensors, remote access via mobile apps, and energy reporting. They can be integrated into larger BMS frameworks or function independently, particularly in retrofitting projects aiming for NZEB targets. Brands like Nest and Ecobee are prominent for their adaptability and integration.

- *Energy Monitoring Dashboards*

These are web-based visual interfaces that display real-time and historical energy consumption data for a building or facility. They enable performance diagnostics and promote occupant engagement. Its features include real-time monitoring of electricity, gas, and water consumption, comparative analytics, abnormal energy use identification, and performance feedback. Advanced dashboards can also use predictive analytics.

➤ *Smart Lighting Systems*

Smart lighting systems are advanced lighting solutions that optimize energy consumption, improve occupant comfort, and reduce operational costs through automation and responsive controls. (Williams, Atkinson, Garbesi, Rubinstein & Van Buskirk, 2012). They are essential for high-performance buildings, providing functional illumination and dynamic interaction with environmental conditions. LED lighting uses 80% less energy than traditional bulbs, achieving 30-60% energy conservation.

- *Light Emitting Diodes (LED) Lighting*

LED lighting is a key component of smart lighting systems due to its high energy efficiency, durability, and controllability. With a lifespan of 25,000-50,000 hours, LEDs are ideal for sustainable building design. They offer instant dimming capabilities, color tuning, and low heat output, allowing for fine-tuned control over light levels. By replacing outdated lighting with LEDs, buildings can significantly reduce baseline energy use, contributing to net-zero energy goals. Occupancy sensors, which use infrared, ultrasonic, or microwave technologies, automatically turn off lights when no one is in a room, ensuring that lights are only on when needed. This prevents energy waste and enhances the overall efficiency of lighting systems.

- *Occupancy Sensors*

Occupancy sensors are devices that detect the presence or absence of people in a space and automatically adjust lighting accordingly. They use infrared, ultrasonic, or microwave technologies to sense motion, ensuring lights are only on when needed. Benefits of occupancy sensors include significant reduction in energy waste, improved user convenience, and extended lamp life. They are often integrated into Building Management Systems (BMS) for centralized monitoring and control in smart buildings. These sensors are particularly useful in areas like restrooms, conference rooms, and classrooms.

- *Daylight Harvesting Systems*

Daylight harvesting is a control strategy that adjusts interior lighting levels based on natural daylight. It uses photocell sensors to dim or turn off electric lights when daylight is sufficient, reducing energy consumption and improving indoor lighting quality. Advantages include enhanced occupant comfort, energy savings, particularly in perimeter zones with windows or skylights, and contributing to LEED and NZEB certifications by reducing lighting loads. When combined with advanced lighting controls and architectural design strategies, daylight harvesting significantly enhances a building's energy performance.

- *Renewable Energy Technologies*

This focuses on the integration of on-site renewable energy technologies to generate clean, sustainable power. This transition reduces energy consumption through efficient design and lowers greenhouse gas emissions. Key renewable energy technologies supporting this transition include solar photovoltaic (PV) systems, solar thermal systems, wind turbines, and battery storage systems. These systems reduce dependence on fossil fuels, lower greenhouse gas emissions, and ensure energy resilience in civil and public buildings.

- *Solar Photovoltaic (PV) Systems*

Solar PV systems are widely used in National Zero Energy Buildings (NZEBS) to convert sunlight into electricity using silicon-based semiconductor materials. These panels can be rooftop-mounted, integrated into the building envelope, or ground-mounted, making them suitable for various building sizes. They offer zero-emission electricity generation, modular scalability, low maintenance requirements, and high reliability. Solar PV is particularly viable in sun-rich regions like Nigeria, where solar irradiance levels are favorable year-round. These systems form the backbone of NZEB energy strategies, allowing buildings to offset their annual electricity demand entirely from solar energy.

- *Solar Thermal Systems*

Solar thermal systems use the sun's heat for domestic hot water production, space heating, and absorption cooling in warm climates. They consist of solar collectors, heat exchangers, and insulated storage tanks, with flat-plate collectors and evacuated tube collectors being common types. These systems reduce dependence on electricity or gas for water heating, lower operational costs, and are simple to install in tropical and subtropical climates. They are particularly relevant in regions with consistent solar exposure, making them ideal for sustainable building design in the Global South.

- *Wind Turbines*

Wind turbines convert wind energy into electricity using aerodynamic rotor blades and can serve as complementary systems to solar PV. They can be installed horizontally or vertically depending on site conditions. However, their viability is highly site-specific, requiring thorough wind resource assessment and consideration of

noise, vibration, and zoning regulations (Ackermann & Söder, 2002).

- *Battery Storage Systems*

Battery storage systems are crucial for achieving full energy independence in New Zero Energy Buildings (NZEBS) by storing excess renewable electricity for later use. Leading technologies include Tesla Powerwall, LG Chem RESU, and Sonnen batteries. Benefits include load shifting, grid independence, and smooth integration of intermittent renewables. In many NZEBs, batteries work with intelligent energy management systems to prioritize storage use, control inverter loads, and maintain energy balance. In developing regions, battery storage enhances the feasibility of renewable-powered buildings, enabling round-the-clock operation without fossil fuel backup.

- *Building Sustainable Material Technology*

Building Sustainable Material Technology is the strategic use of environmentally responsible construction materials to enhance a building's performance, durability, energy efficiency, and occupant comfort. This technology is crucial for Net-Zero Energy Buildings (NZEBS) and sustainable urban development. Sustainable materials reduce the environmental footprint by lowering embodied carbon, improving thermal performance, and contributing to long-term resource efficiency. (Cabeza, Castell, Medrano, Leppers & Zubillaga, 2014). By integrating innovative materials like high-performance insulation, advanced glazing systems, and climate-responsive coatings, architects and engineers can improve passive and active design outcomes, resulting in buildings that consume less energy and maintain better indoor environmental quality.

- *Insulated Concrete Forms (ICFs)*

Insulated Concrete Forms (ICFs) are rigid foam blocks that serve as formwork for reinforced concrete and continuous insulation for walls. They offer exceptional thermal mass, air tightness, and structural integrity, reducing thermal bridging and providing high R-values. ICFs contribute to lower heating and cooling loads, improved sound insulation, durability, and moisture resistance. They are increasingly used in residential and institutional NZEBs due to their ease of installation and compatibility with other sustainable technologies. (Varela & Pereira, 2020).

- *Low-E Coatings*

Low-E coatings are thin, transparent metal layers applied to glazing surfaces, reflecting infrared radiation while allowing visible light to pass through. They minimize solar heat gain in summer and heat loss in winter. There are passive low-e coatings for colder climates and solar control low-e coatings for warmer climates. Low-E glazing is crucial for building envelope efficiency, especially when combined with triple glazing, supporting daylighting strategies without compromising thermal performance.

- *Triple-Glazed Windows*

Consist of three panes of glass separated by insulating gas layers, provide superior thermal insulation compared to double or single glazing. They reduce heat loss and gain while maximizing comfort. Benefits include enhanced acoustic insulation and condensation resistance. Triple glazing is essential for high-performance envelopes in net-zero buildings, particularly in regions with high temperature fluctuations, where energy conservation is critical.

- *Phase Change Materials (PCM)*

Phase Change Materials (PCMs) absorb or release latent heat during phase transitions, regulating indoor temperature by absorbing excess heat during the day and releasing it at night, reducing HVAC reliance and improving indoor thermal comfort in passive design strategies for NZEBs.

- *Green Roof Systems*

Green roofs are becoming more prominent in sustainable public buildings, providing aesthetic, ecological, and thermal benefits in dense urban areas. Cool roof coatings, designed with high solar reflectance and thermal emittance, minimize solar heat gain, keeping roof surfaces cooler than traditional dark roofs. These coatings reduce cooling energy demand, lower indoor air temperatures, and extend roof lifespan. They are particularly beneficial in tropical and subtropical regions like Nigeria, where roof surfaces are exposed to intense solar radiation year-round.

- *Cool Roof Coatings*

Cool roof coatings are designed with high solar reflectance and thermal emittance, often achieved through light-colored coatings or reflective membranes. They minimize solar heat gain, keeping roof surfaces cooler than traditional dark roofs. This reduces cooling energy demand, lowers indoor air temperatures in unconditioned spaces, and extends roof lifespan. Cool roof coatings are particularly beneficial in tropical and subtropical regions

like Nigeria, where roof surfaces are exposed to intense solar radiation.

VI. CASE STUDY OF NZEBs TECHNOLOGY

➤ *National Renewable Energy Laboratory (NREL) Research Support Facility (RSF), USA*

This facility is located in Golden, Colorado, is one of the most celebrated and pioneering Net-Zero Energy Buildings (NZEBs) in the world. Completed in 2010 on an approximate 20,600 m² land size, it remains one of the largest and most energy-efficient office buildings in the world to achieve Net-Zero Energy performance. The RSF was designed under the principle that reducing demand comes before supplying energy, focusing on daylighting, natural ventilation, and thermal mass. The building's east-west orientation, thermal mass, natural ventilation strategy, and advanced energy management system ensure that user behavior aligns with the building's performance goals.

The RSF has successfully operated at Net-Zero Energy, generating as much energy as it consumes over the course of a year. Its Energy Use Intensity (EUI) is approximately 33 kWh/m²/year, which is more than 50% lower than comparable U.S. commercial buildings. Through the integration of technology and design, the building delivers exceptional thermal comfort, excellent indoor air quality, and optimal lighting conditions while maintaining ultra-low operational energy consumption. One of the most innovative aspects of the RSF is its role as a "living laboratory," wired with over 3,000 sensors that track temperature, occupancy, lighting, CO₂ levels, and energy use in real time. The building also introduced a performance-based design-build delivery method, requiring the construction team to guarantee energy performance outcomes.

RSF is cost-effective, being constructed at a cost comparable to conventional office buildings in the U.S. Despite its cutting-edge design, the building was constructed at a cost comparable to conventional office buildings in the U.S.



Fig 2 The Site of the National Renewable Energy Laboratory (NREL), USA
Source: Arch Daily (2010)

➤ *Challenges Deterring Design Strategies and Technologies from Accomplishing Net-Zero Energy Buildings in Civil Building*

- High initial construction and technology costs often exceed conventional budgets, affecting public sector adoption of energy-efficient materials.
- The lack of trained professionals in NZEB-specific design, energy modeling, hindering effective execution and long-term performance management.
- Weak enforcement of building energy codes, lack of performance-based standards, and limited fiscal incentives.
- Geographic and climatic challenges, such as low solar availability, high humidity, or urban density, can hinder the efficiency of both passive and active energy systems.
- Occupant behavior, such as excessive HVAC use and poor lighting habits, affecting efficiency gains from sustainable technologies in buildings.
- Lack of real-time monitoring systems like Building Management Systems (BMS) and energy dashboards hinders performance tracking, optimization, and post-occupancy evaluation.

➤ *Solutions to Improve Design Strategies and Technologies from Accomplishing Net-Zero Energy Buildings in Civil Building*

- Governments should offer financial incentives, tax rebates, and green bonds to offset the initial costs of renewable energy systems, high-efficiency HVAC, and sustainable materials, promoting their wider adoption in the public sector.
- Building Management Systems (BMS) and real-time energy dashboards are being integrated to track consumption, optimize performance, and detect inefficiencies, ensuring buildings maintain net-zero targets throughout their lifecycle.
- Investment in education, certifications, and workshops for architects, engineers, and facility managers will enhance local expertise in passive design, energy modeling, and NZEB technologies, particularly in developing regions.
- Design strategies should consider local climate, materials, and cultural practices, such as maximizing natural ventilation in tropical climates to reduce cooling demand and integrate traditional wisdom with modern sustainability.
- The mandated regulatory frameworks, such as LEED, EDGE, or ASHRAE-compliant, ensure that civil buildings are designed and evaluated based on actual energy outcomes, not just design intentions

➤ *Software Programming and Automation for Smart Energy Management in Net-Zero Buildings:*

Highlight the portion of software engineering in enhancing energy use, integrating renewable systems, and allowing real-time mechanism in smart civil buildings. Mention tools like Building Information Modeling (BIM), energy simulation software, and IoT-based energy management platforms. It includes:

- Software-Driven Energy Simulation. /
- Smart Control System.
- Real-time Monitoring and IoT Integration.
- Machine Learning for Predictive Optimization.

VII. CONCLUSION

Achieving Net-Zero Energy Buildings (NZEBs) in civil architecture is a crucial strategy to mitigate climate change, improve energy security, and enhance public infrastructure quality. The integration of innovative design strategies and cutting-edge technologies plays a critical role in shaping buildings that produce as much energy as they consume over a defined period. Passive design approaches, such as optimal orientation, natural ventilation, daylighting, and thermal mass, reduce energy demand at the source. Active systems, such as energy-efficient HVAC systems, renewable energy technologies like solar photovoltaic and wind, and smart building automation systems, optimize building performance in real time. Sustainable material technologies, such as high-performance glazing and cool roofs, support energy conservation while enhancing indoor comfort and durability. However, the transition to NZEBs in civil buildings faces challenges such as high capital costs, lack of skilled professionals, weak policy enforcement, and behavioral inefficiencies. Overcoming these barriers requires a multidisciplinary and policy-driven approach, including investment in capacity building, adoption of context-specific design frameworks, integration of monitoring tools, and provision of financial incentives.

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