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Net-Zero Carbon Buildings: Integration of Renewable Energy, Energy Efficiency and Sustainable Construction Practices - A Literature Review

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Abstract: Buildings use energy every day and also require large amounts of materials such as cement, steel, glass and bricks. These activities create greenhouse-gas emissions. A net-zero energy building mainly tries to balance the energy it uses with renewable energy. A net-zero carbon building has a wider aim: it considers carbon emissions from building operation and, when a whole-life boundary is used, from materials, construction, repair, replacement and end-of-life stages. This review explains how renewable energy, energy efficiency and sustainable construction can work together. The selected studies show that reducing energy demand should come first. Solar power and other suitable renewable systems can then meet part of the remaining demand. At the same time, designers should reduce material use, choose lower-carbon products, reuse resources and check the full life cycle of the building. The review also discusses Indian building-energy rules and the IGBC Net Zero Carbon rating system. It concludes that a clear carbon boundary, local climate data and life-cycle assessment are needed before a building can make a reliable net-zero carbon claim. [1,2,3,13,14]

Keywords: Net-zero carbon buildings; renewable energy; energy efficiency; embodied carbon; operational carbon; sustainable construction; life-cycle assessment; India.

I. INTRODUCTION

Buildings are needed for homes, education, offices, health care and many other activities. However, buildings also use electricity and fuels for lighting, cooling, heating, ventilation, lifts and equipment. Carbon emissions are also created before a building is used. These emissions come from the production of cement, steel, bricks, glass and other materials, as well as transport and construction work. Repair, replacement and demolition can create further emissions. For this reason, building carbon should not be judged only by the electricity bill. [2,3,10,16]

The terms net-zero energy building (NZEB) and net-zero carbon building (NZCB) are related, but they are not the same. An NZEB is mainly judged by an energy balance within a stated boundary and time period. An NZCB is judged by greenhouse-gas emissions. A building may produce as much energy as it uses and still have high carbon emissions from concrete, steel and other materials. Whole-life carbon assessment is therefore important. [1,12,13]

This paper reviews three connected areas: renewable energy, energy efficiency and sustainable construction. It also explains why these measures should be planned together and discusses their use in the Indian context.

II. AIM AND REVIEW APPROACH

The aim of this paper is to explain simple and practical ways to reduce carbon emissions from buildings. The review uses selected peer-reviewed journal papers published mainly between 2020 and 2026, along with official Indian building guidance. The papers were selected because they discuss one or more of the following areas: net-zero carbon definitions, renewable energy, energy-efficient design, embodied carbon, building retrofits and life-cycle assessment.

The selected studies were compared and their main points were written in simple language. This paper is a focused narrative review. It is not a complete systematic review and does not claim to include every paper published on the subject. The main purpose is to bring together useful findings for students and building-design practice.

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III. UNDERSTANDING NET-ZERO CARBON BUILDINGS

A. Operational Carbon

Operational carbon means emissions caused while a building is in use. It mainly comes from the electricity and fuels used for lighting, cooling, heating, ventilation, water heating and equipment. The amount depends on the building design, how people use the building and how clean the electricity supply is. Better insulation, efficient equipment and renewable electricity can reduce these emissions. [1,5,8]

B. Embodied Carbon

Embodied carbon means emissions linked to the materials and work needed to create and maintain a building. It can include mining and processing raw materials, making cement and steel, transporting products, construction work, repairs, replacement and disposal. These emissions may occur before people start using the building. They can be reduced by using less material, selecting lower-carbon products, reusing parts and planning for a longer service life. [3,9,14,16,17]

C. Net-Zero Energy and Net-Zero Carbon

Net-zero energy focuses on the balance between energy use and renewable energy generation. Net-zero carbon focuses on the balance of greenhouse-gas emissions within a stated boundary. The result depends on which life-cycle stages are counted, how electricity is measured and how any remaining emissions are treated. A paper or project should clearly state these rules instead of using the words “net zero” without an explanation. [1,13,18]

IV. INTEGRATION OF RENEWABLE ENERGY

Renewable energy can reduce emissions from the electricity and heat used in a building. Solar photovoltaic (PV) panels are widely used because they can be placed on rooftops, parking shades and some building surfaces. Building-integrated photovoltaics (BIPV) form part of the roof, façade or shading system. Their output depends on the available area, direction, shading, local weather and the building's energy demand. [4,5]

Solar water heaters can provide hot water with less electricity or fuel. Heat pumps can provide heating and cooling efficiently when they use low-carbon electricity. Small wind systems may be useful at selected sites, but wind speed, noise, safety and maintenance must be checked before installation. A technology should be selected according to local conditions, not only because it is available.

Solar and wind power do not produce electricity at every hour. Batteries, thermal storage, smart controls and grid connections can help match supply with demand. Storage also has a material and manufacturing impact, so its size and service life should be considered. The first step should be to reduce unnecessary energy use; renewable systems can then be sized for the remaining demand. [5,8,15]

V. ENERGY-EFFICIENCY STRATEGIES

Energy efficiency means providing the same service while using less energy. Passive design is a useful starting point because it reduces the need for mechanical systems. Important measures include choosing a suitable building orientation, providing shade, using daylight, planning natural ventilation, selecting suitable windows and improving roof and wall insulation. These measures should match the local climate. A design that works well in a hot and humid city may not work in a cold hill area. [1,7]

Active measures include LED lighting, efficient fans and pumps, high-efficiency air-conditioning, suitable heat pumps, occupancy sensors, timers and energy meters. Building-management systems can help control equipment according to use and weather. Regular maintenance is also important because poorly maintained systems can use more energy than expected. [6,8]

Energy saving should not reduce indoor comfort or health. Buildings still need enough fresh air, good daylight, safe temperatures and suitable indoor conditions. A successful design should balance energy use with the needs of the people who use the building.

VI. SUSTAINABLE CONSTRUCTION PRACTICES AND EMBODIED CARBON

The choice and quantity of materials have a major effect on embodied carbon. Concrete, steel and aluminium can have high emissions because their production needs energy and industrial processes. Designers can reduce this impact by avoiding unnecessary material, using efficient structural layouts and selecting products with reliable environmental

information. Lower-carbon concrete, recycled steel and suitable alternative materials may help, but their strength, durability, fire safety, availability and transport distance must be checked. [3,9,14,16]

Reuse is often better than sending usable materials to waste. Existing buildings and components should be checked for possible repair or reuse before demolition. Construction and demolition waste can be separated so that suitable materials are reused or recycled. Local materials may reduce transport impacts when their production and performance are also suitable. A material should not be called low-carbon only because it is natural or locally available; its full impact should be checked.

A long-lasting building can avoid repeated material replacement. Good detailing, protection from moisture, suitable maintenance and flexible planning can help extend building life. The design should also allow future repair and changes in use. [2,3,14]

VII. LIFE-CYCLE ASSESSMENT AND CARBON ACCOUNTING

Life-cycle assessment (LCA) is a method used to study the environmental impact of a product or building across its life. For a building, the study may cover material production, transport, construction, use, repair, replacement, demolition and recycling. A whole-life carbon study uses this information to estimate greenhouse-gas emissions across the chosen stages. [10,11,17]

The result depends on the study boundary, building life, material quantities, electricity emission factors and data quality. Two studies may report different values because they use different assumptions. Environmental product declarations and local material data can improve the quality of the calculation. LCA is most useful when it is started during early design, because major choices about size, layout and materials are still open at that stage. [10,12,17]

Carbon offsets should be reported separately from direct emission reductions. A building should first reduce energy demand and material-related emissions as far as practical. Any remaining emissions and the method used to address them should be clearly stated. A net-zero claim is only meaningful when the boundary and calculation method are transparent. [13,18]

VIII. INDIAN CONTEXT

India has a wide range of climates, from hot and dry regions to warm-humid coastal areas and cold hill regions. Building design should respond to local temperature, rainfall, sunlight, wind and user needs. The same design cannot be applied in every state. Passive design and efficient building services can reduce demand, while suitable solar systems can supply part of the remaining energy.

The Bureau of Energy Efficiency (BEE) published the Energy Conservation Building Code (ECBC) 2017 for commercial buildings within its stated scope. The code covers areas such as the building envelope, heating and cooling systems, lighting, electrical systems and renewable-energy provisions. It provides different levels of energy performance for buildings that follow the code. [19]

The Indian Green Building Council (IGBC) also provides a Net Zero Carbon rating system. Its published scope includes whole-building life-cycle analysis, embodied carbon, operational carbon, passive architecture, energy efficiency, waste diversion and renewable-energy-related measures. The system distinguishes between the design and construction phase and the operation phase. This shows that carbon assessment is broader than checking the annual electricity bill. [18]

For colleges, offices and other institutional buildings, a practical starting point is to record energy use, study the roof and site for solar potential, improve lighting and cooling systems, reduce water and material waste, and collect data on major construction materials. These steps can help prepare a realistic carbon-reduction plan.

IX. CHALLENGES AND FUTURE SCOPE

The main challenges are the high first cost of some technologies, limited local carbon data, different methods of calculating emissions and a shortage of trained people. A building may also use more energy than expected if the systems are not operated correctly. Renewable systems need maintenance, and their panels, inverters and batteries will need replacement at some point. These effects should be included in whole-life planning. [2,8,9,13]

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Future work should prepare better regional data for Indian construction materials, compare new buildings with retrofits, and study the performance of buildings after people start using them. More research is also needed on low-carbon concrete, steel, reuse of building components, building-integrated solar systems and simple LCA tools that designers can use at the early stage. [3,10,14,15]

X. CONCLUSION

Net-zero carbon buildings need more than solar panels. They require lower energy demand, suitable renewable energy and careful control of emissions from construction materials. Passive design and efficient equipment reduce operational energy. Solar PV and other suitable renewable systems can supply part of the remaining demand. Lower-carbon materials, reuse, recycling and long building life can reduce embodied carbon.

The reviewed studies support one clear approach: reduce demand first, choose renewable systems according to the site, reduce material-related emissions and assess the full life cycle. The calculation method and carbon boundary should always be stated. In India, building codes and rating systems provide useful guidance, but local climate, reliable data, cost and proper operation remain important. A building can make a credible net-zero carbon claim only when its emissions are measured and reported in a clear way.

XI. LITERATURE REVIEW

The following studies were selected because they directly relate to net-zero carbon buildings, renewable energy, energy efficiency, sustainable construction or life-cycle assessment. Each summary gives the main point of the published work in simple language.

Lou and Hsieh (2024). "Towards Zero: A Review on Strategies in Achieving Net-Zero-Energy and Net-Zero-Carbon Buildings."
This review compares the ideas of net-zero energy and net-zero carbon buildings. It explains how energy-saving design and renewable energy can reduce emissions. It also shows why material-related emissions should be included when the aim is net-zero carbon. [1]

Myint et al. (2025). "Net Zero Carbon Buildings: A Review on Recent Advances, Knowledge Gaps and Research Directions."
The authors review recent methods for reducing both operational and embodied carbon. They discuss energy efficiency, renewable energy, low-carbon materials and circular use of resources. The paper also points out that cost, policy and local knowledge can affect the use of these methods. [2]

Wang et al. (2024). "A Comprehensive Review of Building Lifecycle Carbon Emissions and Reduction Approaches."
This study looks at emissions from material production, transport, construction, building use and end-of-life work. It notes that transport and construction-site emissions are not always measured well. It supports the need to study the whole life of a building instead of only its energy use. [3]

Kong et al. (2023). "Application of Building Integrated Photovoltaic (BIPV) in Net-Zero Energy Buildings."
This review studies solar panels that are part of a building roof, façade or other surface. It explains that BIPV performance depends on the building shape, window area, sunlight and shading. It also notes that roof panels alone may not meet the full electricity demand of some buildings. [4]

Ahmed et al. (2022). "Assessment of the Renewable Energy Generation towards Net-Zero Energy Buildings: A Review."
The authors discuss different renewable-energy options for net-zero energy buildings. Their review explains that a technology should be judged by more than its energy output. Cost, life-cycle impact and the needs of the building should also be checked before choosing a system. [5]

Ibrahim et al. (2024). "Building Retrofitting towards Net Zero Energy: A Review."
This paper reviews ways to improve existing buildings through passive design, efficient equipment and renewable energy. It compares measures used in different building case studies. The authors show that the best retrofit depends on the local climate and how people use the building. [6]

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Maghami et al. (2025). "Net Zero Energy Buildings: An Overview of Passive and Active Designs."
This review studies passive and active methods used in net-zero energy buildings. Passive measures reduce the need for heating and cooling, while active systems improve the performance of equipment. The paper gives a broad view of design trends and the problems that limit wider use. [7]

Parvin et al. (2025). "Building Energy Technologies towards Achieving Net-Zero Pathway: A Comprehensive Review, Challenges and Future Directions."
The authors discuss efficient building services, renewable-energy systems, storage and links with the power grid. The paper shows that energy technologies work best when they are planned as one system. It also discusses the technical and practical issues that need further study. [8]

Shi et al. (2025). "Assessment and Reduction of Embodied Carbon Emissions in Buildings: A Systematic Literature Review of Recent Advances."
This review examines recent studies on how to measure and reduce embodied carbon. It identifies early design decisions and material selection as important chances to reduce emissions. It also notes that more consistent data and methods are needed across regions. [9]

Prideaux et al. (2024). "Integrating Life Cycle Assessment into the Building Design Process - A Review."
This review explains how LCA can be used during building design. It discusses simplified, detailed and step-by-step methods. The authors point out that LCA is more useful when it supports design decisions early, rather than being used only after the design is complete. [10]

Alaux et al. (2024). "Whole-Life Greenhouse Gas Emission Reduction and Removal Strategies for Buildings."
The authors identify strategies for reducing emissions across the full life of buildings. Their review brings together measures for design, construction, operation and later stages. It supports the idea that a net-zero plan should not focus on one stage alone. [11]

Kayaçetin and Hozatlı (2024). "Whole Life Carbon Assessment of Representative Building Typologies for Nearly Zero Energy Building Definitions."
This study compares whole-life carbon for different building types and technical systems. It shows that improving energy performance can reduce whole-life emissions, but extra materials and equipment may also add embodied carbon. The balance should therefore be checked for each building type. [12]

Wang and Lin (2025). "A Comprehensive Review on Definitions, Development, and Policies of Net-Zero Carbon Buildings."
This review compares how net-zero carbon buildings are defined in different places. It also discusses policies, targets and certification systems. The paper is useful because it shows why the boundary and calculation rules must be clear when a building is called net zero. [13]

Watari et al. (2024). "Net-Zero Embodied Carbon in Buildings with Today's Available Technologies."
This study examines ways to reduce emissions from building materials. It discusses lower-carbon steel and concrete, timber structures, better design and longer building life. The authors show that existing technologies can make a large contribution, although they must be used with suitable planning and policy. [14]

Butt et al. (2026). "Net-Zero Carbon Buildings: A Review of Operational-Embodied Carbon Trade-Offs and Building-Integrated Renewables."
This recent review studies the connection between building energy systems and embodied carbon. It explains that solar panels, storage and smart systems can reduce operational emissions, but their production and replacement also have impacts. Their benefits should be checked over the full service life. [15]

Röck et al. (2020). "Embodied GHG Emissions of Buildings - The Hidden Challenge for Effective Climate Change Mitigation."
The authors analyse more than 650 building life-cycle studies. Their work shows that as buildings become more energy efficient, emissions from materials can become a larger part of the total. This is an important reason to measure operational and embodied carbon together. [16]

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