



Beyond Net Zero Energy: A Life Cycle Assessment of Carbon Emissions and Environmental Sustainability in Buildings(A-Review)

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ABSTRACT:

Buildings are energy intensive and can emit GHGs during their construction and throughout their lifespan. This paper collates the results of five research papers focused on: Net-zero energy buildings, Life-cycle carbon, Solar PV, Heating & Cooling options, and City-scale planning. Finally, the studies reveal that it is not necessarily the case that a building would have zero emissions for its entire life if it produced sufficient amounts of renewable electricity to offset its annual energy consumption. Materials, construction, transport, equipment replacement, maintenance and demolition also are important. A case study performed in Ahmedabad, India, showed 866 tonnes of carbon dioxide equivalent over 60 years despite the building's net zero operational energy status in the case study. In Canada, research has shown that emissions can be reduced with heat pumps and solar panels, however, the optimal system can vary depending on local climate and costs. A city-wide study, using geographic information systems and building information modelling, has revealed significant life-cycle effects in transitioning to 'urban Net zero'. The study concluded that the rooftop solar panels could supply a significant amount of electricity demand in the apartment buildings in Jordan and the study cases were deemed to be cost-effective. The collection of papers provide an approach that can be implemented: minimise energy use, select appropriate equipment, utilise renewable energy, consider lower impact material and evaluate all life cycle stages. There's also a need for improved local information and straightforward guidelines. This paper is an article-based discussion, and is not based on new experimental measurement.

Key Words: Net zero energy buildings; life cycle assessment (LCA); life cycle carbon emissions; embodied carbon; renewable energy; energy efficient HVAC systems; building sustainability.

Introduction:

While buildings are essential to the daily life, they also consume energy and generate greenhouse gases. Lighting, appliances, heating, cooling and ventilation require electricity. The materials for buildings, such as cement, steel, glass, and insulation, also require energy production. Other building materials, like cement, steel, glass, and insulation, use energy to be produced, as do materials that are transported to the construction site. Subsequent repairs, replacement equipment, renovations and demolitions to buildings can also be required later. Therefore, the environmental impact of a building can be assessed not only by the electricity bill once the occupants have occupied.

The term "net zero energy building" typically refers to a building that produces as much renewable energy as it consumes within a specified timeframe, usually a year. This energy can be produced by PV panels. A building, however, might use the same amount of energy each year and yet its energy consumption could be associated with energy consumed in the building materials and equipment used to build the building. The former and latter emissions are sometimes referred to as 'embodied emissions' or 'life-cycle emissions'. A more comprehensive evaluation then takes into account the entire life cycle of a building, from the raw materials to construction, to operation, maintenance, replacement and end-of-life treatment.

Life-cycle assessment (LCA) is a way to approximate these impacts at each of the stages. It can assist those involved in designing and owning a facility to compare options that might appear comparable at first glance but when only energy costs are taken into account. For instance, a system with a high capital cost might result in fewer emissions and less energy usage in the long run. An alternative system may be a better choice in another climate. Results are affected by local weather, type of electricity supply, type of building use, building material, assumed lifespan of the building, and the conditions used for the assessment.

The five studies reviewed in this paper are of a different aspect of the same problem. Jain and Rawal (2022) evaluate the energy balance of an Indian building that has been designed to be net zero, and demonstrate that the operational energy balance does not equal the lifetime carbon balance. Kathiravel et al. (2024) make a comparison of HVAC systems under different climate conditions in Canada, employing BIM, energy simulation, life-cycle costing and uncertainty methods. This paper, by Abu Qadourah (2022), examines the energy production and economic benefits of rooftop solar PV panels in apartment buildings in Jordan. Li and Feng (2025) explore net-zero strategies at the city level using a combination of geographic information systems, building information modelling and LCA. Li, Widén and Shadram (2025) provide an overview of research and policies on net zero energy and emissions

buildings in the lifecycle and highlight areas for further research. Note a single uploaded PDF is a duplicate of the city-scale study and is therefore only counted once here.

This paper aims to provide a simple description of the key conclusions of these studies, to compare the conclusions from the various studies where possible and to outline some useful actions for the construction of projects. The point being that solar panels and efficient equipment are not enough for lower-carbon buildings. They need decisions to be made taking into account energy demand, material impacts, local climate, financial costs, equipment life, and a full life cycle. This paper does not purport to be a new field experiment or a comprehensive review of all research found.

Literature Review:

The reviewed studies centre around various scales in the construction of sustainability but all share the perspective that sustainability decisions should not be made based on the energy use per year.

Jain and Rawal (2022) experimentally evaluated a building at CEPT University, Ahmedabad, India that is designed to achieve Net Zero Energy status. They took into account emissions from building materials, building operation and end-of-life processes in the course of their life-cycle assessment. The study estimated that 866 tonnes of carbon dioxide equivalent will be emitted over the 60-year life, as defined by the study's assumptions. It is clear that a building can be energy neutral for a year, but have emissions over the life of the building. The outcome is influenced by the definition of "system boundaries," the quality of the data, the amount of electricity produced that is sold to the grid, and the inclusion of recycling benefits. The authors emphasize the availability of more life-cycle information for India; materials and construction techniques vary across countries.

Kathiravel et al. (2024) analysed 36 scenarios with HVAC systems and 6 climate conditions for Canada. In the paper, the natural gas furnace was compared to air-source heat pumps and ground-source heat pumps with and without PV panels. It concluded that cooler climates increase energy demand. Overall, GHP's typically consumed less electricity than ASHP's; this energy savings increased for colder regions. The solar panels had a 30-50% lower modelled warming impact compared to scenarios with natural gas furnaces, which had higher emissions. However, the initial cost of a ground-source heat pump might be higher. The most appropriate option will, however, depend on local climate and the cost/environmental impact. The paper also presents an example of BIM and uncertainty methods to organise data and compare options.

Abu Qadourah (2022) estimated the performance of rooftop PV at apartment buildings in various climatic regions of Jordan. The study conducted a simulation to compare different panel directions, panel tilts, electricity produced, payback period, and net present value. In the modeled scenarios, solar panels could meet 40-87% of current electricity demand and payback was estimated at 3.4-5.6 years. The best result in the comparison was achieved from the east and west facing panels with a tilt of 7°. The results are subject to the locations, taxes, roof conditions, and assumptions about the system used, and cannot be guaranteed on all buildings. However, the study indicates that the installation of rooftop solar can potentially be both energy and economic beneficial when tailored to local conditions.

Li and Feng (2025) proposed a city-scale method based on the integration of the geographic information system (GIS), building information modelling (BIM), and life cycle assessment (LCA). They applied their case study in Richmond, British Columbia, where they compared the two scenarios: usual urban development and an urban net zero building scenario. The scenario modelled achieved a global warming potential reduction of approximately 45%, and a reduction of approximately 40% in fossil energy demand. The method also identified building types and locations where the improvements have the potential to have a significant impact. But, the paper cautions, impact reductions in one phase can lead to impacts in other areas, such as in the material supply or end-of-life processes. This facilitates the consideration of several buildings in one, yet accounting for impacts from material, operation and disposal.

Li, Widén, and Shadram (2025) summarised research and policies regarding buildings with life-cycle net-zero energy and emissions. They clarify that the field has come a long way from energy balance annually to now encompassing embodied impacts across the building's lifespan. Their review reveals that research often fails to account for treatment, end-of-life treatment, equipment replacement and maintenance. There is a need for additional data in non-residential buildings, in climates that are less represented, and for longer building lifetimes and passive design, efficient systems and renewable energy. Use of digital tools like BIM, optimisation, sensitivity analysis and artificial intelligence can assist but more research with actual measured data and different building types is required. The authors further call for better policies and regulations that apply to existing buildings as well as new construction.

All of the studies conclude that renewable energy is helpful but that it can not eliminate all emissions. Equipment shall be appropriate to the local climate and cost and environmental effects shall be taken into account. The results of life cycle depend on data quality, assessment boundaries and BIM and GIS can be used to identify opportunities for improvement. The numbers of studies should not be interpreted as coming from a common experiment because they are from different locations and different experimental design. Together their message is that a whole-life perspective to building decisions is required.

Conclusion:

Having "zero operational energy" should not be the sole measure of sustainability for a building. Environmental impacts should also be considered for its

materials, construction, energy, use, maintenance, equipment replacement and end of life. The reviewed studies demonstrate that the use of energy-efficient design, appropriate heat pumps, rooftop solar panels and low impact materials can minimise the building's environmental footprint. The effectiveness depends on local climate, building characteristics, costs, assessment methods, however. The Ahmedabad study demonstrates the difference between the two types of energy—operational energy and life cycle energy—and the environmental and economic advantages of using the right technology, as depicted in the Canadian and Jordan studies. These results, however, do not permit one-to-one comparisons because of the numerous differences regarding the location of the studies, the assumptions made, and the scope of the systems. Further work needs to be done on additional building types, climates and on actual operating data. In conclusion, the energy demand reduction, selection of appropriate clean technologies, and life cycle building approach are crucial in the development of environmentally responsible and cost-effective buildings.

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