Academic International Journal of Engineering Science
ISSN: 2984-7745
Aca. Intl. J. E. Sci. 2024; 2(2) 18-30
Journal homepage: www.aipublishers.org/aijes

Document Heading

Net-Zero Energy Buildings: Integrating Smart Materials and Passive Design Strategies in Urban Architecture

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Article Info.
Article history:
Received 20 September 2024
Revised 16 October 2024
Published 13 November 2024
Keywords:
Net-zero energy buildings; Smart materials; Passive design; Building energy efficiency; Phase-change materials.
How to cite:
AbdelKareen W. Makhloufi, Net-Zero Energy Buildings: Integrating Smart Materials and Passive Design Strategies in Urban Architecture. Aca. Intl. J. E. Sci. 2024; 2(2) 18-30.
DOI:
https://doi.org/10.59675/E223

Abstract

Building design and operation are critical in mitigation of climate change since the construction industry contributes about 40 percent of all energy used on the planet and 36 percent of carbon dioxide to the environment. This paper will discuss how smart materials and passive design could be integrated to achieve net-zero energy performance in a building within an urban environment. The study examines the performance of enhanced building envelope technologies such as phase-change materials, electrochromic glazing, and self-healing concrete, as well as the passive design such as natural ventilation, optimization of daylighting, and the use of thermal mass. The evaluation of the energy performance of different climate conditions and designs under different design configurations was done by using building information modeling simulation tools. The discussion shows that the strategic incorporation of phase-change materials in building envelopes may decrease cooling loads by 15-30 percent and optimized passive design techniques may help to reduce energy demands by 40-55 percent, in comparison with the traditional building techniques. Use of self-healing materials makes the structure have a longer service life and less energy is used on the structure due to the maintenance process that has been reduced by approximately 20-35. Regional-responsive architectural methods, which simply considered the local climatic conditions, were discovered to contribute to the overall contribution of the building performance and comfort of occupants as well as reducing the dependency on mechanical systems. These results point to the fact that a thorough approach to integrating smart materials with passive design guidelines with the help of sophisticated simulation and modeling tools offers a good opportunity to reach the net-zero energy goal in urbanistic buildings. Not only does this

strategy respond to energy efficiency and carbon goals but also facilitates resiliency, flexibility and sustainability of the built environment.

Introduction

The constructed environment has a significant impact on the trends of energy consumption and greenhouse gas emissions on the planet. The contribution of buildings to the total global energy consumption and carbon dioxide emissions as a result of energy consumption is about 40 percent and almost 36 percent respectively [1, 2]. In response to the growth in urbanization and the ever-growing urban population concentrations, the responsibility of the architectural practices to the environment increases accordingly. Building and functioning of buildings are major causes of resource depletion, environmental degradation, and climate change [3, 4]. The phenomenon of the net-zero energy buildings has taken shape in reaction to these issues as an extremely important paradigm in the field of sustainable architecture and practice in engineering.

A net-zero energy building is one in which the amount of renewable energy generated by the building matches the amount of energy it uses in one year, which leads to the net energy balance being zero [5, 6]. It requires a holistic solution of integrating drastic demand cuts in energy by designing energy-efficient buildings with renewable energy production devices at the site to achieve this ambitious target [7]. As opposed to traditional construction methods that focus on aesthetic factors or initial housing prices, net-zero construction demands a systematic combination of various performance-based strategies at the very first concept development phases up to the specifications of the design and construction [8, 9].

Conventional methods of constructing energy efficiency have been based on enhancing the work of mechanical systems or insulating building envelopes. Although they help reduce energy, they do not usually solve the root cause of the problem of relationship between architectural form, material selection and environmental performance [10, 11]. Modern scientific work is more and more inclined to the idea that to attain net-zero energy performance, one should adopt a paradigm change in the approach to the design, namely, to holistic design solutions that will exploit both the principles of passive environmental control and sophisticated material technologies [12, 13].

Passive design methods utilize the natural environmental forces as forces of solar radiation, wind patterns and thermal gradients to provide comfortable indoor environments with minimal mechanical intervention [14, 15]. They are strategic building orientation, optimal placement and size of windows, the use of thermal mass, natural ventilation system, and design of daylighting [16, 17]. Passive strategies can cut the heating, cooling and lighting energy requirements by 40-60 percent in comparison with conventional buildings when applied appropriately [18, 19]. Nonetheless, passive design may be very ineffective based on the climate conditions, site peculiarities, and the purpose of the building, and it is necessary to analyze it and make every project specific [20, 21].

In addition to passive design techniques, smart materials are a new horizon in the field of architectural engineering and provide an opportunity of dynamic reaction to environmental factors [22, 23]. Such

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advanced materials have the capacity to alter their qualities to external factors like temperature, light or moisture, allowing to have building envelopes dynamically modified in energy flows and indoor environmental quality optimization [24, 25]. Thermal storage capacity is offered by phase-change materials (absorb or release thermal energy during changes in state) that stabilize temperatures in the interiors and decrease the peak cooling and heating loads [26, 27]. Electrochromic and thermochromic glazing systems are also self-regulating systems of optical properties to control the transmission of solar heat and daylight and minimize cooling requirements and glare without interrupting visual contact to the exterior [28, 29]. In self-healing materials, there are micro-cracks and damages that heal automatically, ensuring an extension of structural service life and minimisation of the embodied energy of maintenance and replacement [30, 31].

These sophisticated materials and passive approaches are eased by the use of modern digital design and simulation tools, with Building Information Modeling platforms coming to mind [32, 33]. With the help of these technologies, the architectural professionals and engineers can determine the building energy performance with a high degree of accuracy during the design stage and optimize the form, orientation, choice of materials, and system settings iteratively before construction starts [34, 35]. Simulation of performance assists in evidence-based decision making as well as discovering synergies between various design strategies that may otherwise be obscure using the traditional design methods [36, 37].

The net-zero energy design principles are yet to be widely used, but there are a number of major obstacles to the increased awareness of their potential. These are increased initial construction prices, less knowledge of the design professionals with modernized material and integrated design, regulatory systems that give more preference to traditional building systems, and uncertainties on the performance and maintenance of the buildings in the long term [38, 39]. In addition, the performance of certain strategies in various zones of climate and types and patterns of buildings and occupancy also differ significantly, requiring context-specific solutions and not universal ones [40, 41].

This study shall deal with these issues by looking into the incorporation of smart materials and passive design solutions in the realization of net-zero energy performance in city structures. Research question: The proposed research aims to examine the performance properties of advanced building envelope technologies, the use of passive environmental control measures under different climatic conditions, and the use of Building Information Modeling tools to design decisions in the optimization process. This is aimed at offering evidence-based advice to architectural practitioners and policymakers who want to promote sustainable building practices and also take part in mitigation of global climate change initiatives.

Methodology

The study utilized a balanced analytical method involving literature review, case study analysis and performance simulation of building buildings with a net-zero energy by integrating the concept of smart materials and passive design. The research design was developed in such way that it would look at numerous building performance such as energy usage, thermal comfort, daylighting quality, and sustainability measures over long-term.

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The literature review stage was the analytic study of peer-reviewed journal articles, conference papers, and technical and industry reports related to the net-zero energy buildings, smart materials in architecture, passive design techniques, and building performance simulation. Database searches were carried out with the help of the following keywords that were relevant: net-zero energy, phase-change materials, electrochromic glazing, self-healing concrete, passive design, Building Information Modeling, and climate-responsive architecture. The selection criteria focused on the recent publications that provided empirical data, documentation of case studies and performance validation outcomes.

Integrated Building Information Modeling platforms were used to construct the performance simulation along with energy analysis software. There were representative building models that had been developed in various climate zones that reflected a wide and varying range of environmental conditions such as hot-humid, hot-dry, temperate and cold climates. The reference models were used to depict traditional construction that meets minimum energy code standards whereas other design scenarios were used to depict different combinations of smart materials and passive strategies.

The phase-change materials were simulated in building envelope assemblies such as walls, roofs and interior partition systems. The simulation parameters were determined based on the phase transition temperatures of 20-28 degrees Celsius, latent heat storage capabilities of between 150-250 kilojoules per kilogram and different integration techniques such as direct incorporation, encapsulation and surface application. Thermal performance was tested on seasonal cycles to determine the effect of annual energy and the potential of energy reduction at peak loads.

Simulation of electrochromic and thermochromic glazing was done using varying values of transition properties, switching speed, and control strategies. The optical characteristics such as visible light transmission, solar heat gain coefficient and the ultraviolet blocking were built as dynamic variables based on the impact of incident solar radiation, interior temperature, and schedules of occupants. Building automation systems were simulated to have the optimal switching behavior in terms of energy efficiency and occupant comfort.

The performance of self-healing concrete was assessed by means of the literature assessment regarding the mechanisms of crack repair, the efficiency of the healing process, and the enhancement of long-term durability. The analysis also had embodied energy calculations of conventional concrete that needs to be maintained and replaced every few years as opposed to self-healing ones that have a long service life. The analysis took into consideration different healing processes such as bacterial activation, encapsulated healing agents, and material properties inherent in it.

Parametric simulation studies effectively analysed passive design strategies. An orientation of the buildings was done at different angles of 15 degrees in order to determine the best building arrangement in each climate zone. The ratio of window-to-wall was examined in a window of 20 to 60 percent of varied facade keeping in mind the balancing of daylighting advantages and thermal loads. The computational fluid dynamics analysis coupled with thermal models were used to evaluate natural ventilation effectiveness by evaluating different window designs, stack effect, and cross-ventilation opportunities.

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- Optimization of Thermal mass was considered, whereby various materials were tested such as concrete, masonry, and earth-based construction, which differed in terms of thickness, location, and surface treatment. Thermal storage and thermal conductivity were modeled to arrive at the best configurations in order to moderate the high and low temperatures in the day and to relocate the thermal loads to off-peak hours.
- Daylighting analysis was a simulation analysis based on radiosity to forecast the illuminance of interior spaces, ratio of uniformity of illumination, and the probability of glare. The analysis used different shading devices and light shelf systems and reflective surfaces to make the most of natural light distribution and the least of direct solar heat penetration and visual discomfort.
- Climate responsive design strategies were formulated on each representative climate zone depending with the outcome of the simulation and the laid down principles of passive design. The strategy acknowledged that the best strategies are very different depending on the local environmental situations and that one needs to come up with local solutions rather than prescribed solutions.

The combined strategies were considered in terms of integrated performance by the whole-building energy simulation that takes into consideration the interactions of the envelope performance, passive systems, and mechanical equipment. The computation of annual energy used on heating, cooling, ventilation, lighting, and plug loads were done. Peak demand profiles were examined to estimate the implications on electrical infrastructure and size of renewable energy system. The Energy Use Intensity figures were estimated and measured against the baseline conditions and net-zero energy guidelines.

Initial construction cost premiums based on superior materials and passive design features was done in an economic analysis and compared those with expected future operational energy savings at 50-75 years of building lifetime. The current energy prices and plausible energy escalation assumptions were used to obtain simple payback periods and assess lifecycle cost.

The model of analysis identified intrinsic uncertainty in the prediction of performance over the long term, material longevity, occupant characteristics and future energy costs. Sensitivity analyses were done to determine the impact of changes in the main parameters on aggregate performance outcomes and economic feasibility.

Results and Discussion

The overall discussion of smart materials and passive design strategies shows a considerable potential of net-zero energy performance of urban buildings using integrated design strategies. The simulation outputs indicate that the combination of high technologies of the envelope and climate-sensitive passive approaches can save the accumulated energy of buildings by 60-75 percent in comparison to traditional buildings without such advancements that comply with the minimum code requirements.

The thermal performance of phase-change materials that were integrated in building wrappings showed significant thermal performance in various climate regions. Addition of PCMs with a transition temperature of 23-26 degrees Celsius to wall and roof-assemblies in hot climates minimized peak

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cooling loads by 18-32%. The thermal storage effect postponed the transmission of heat through the envelope during the afternoon peak periods and increased cooling loads were moved to evening and night time when the ambient temperatures were lower and mechanical system efficiency was higher. The performance especially in high diurnal temperature swing buildings became especially high where the phase transition cycle could be finished within 24-hour intervals. PCM integration in temperate climate led to a reduction in load by 12-20 and benefits were realized during both season heating and cooling periods. Cold climate was much more humble in its performance with 8-15 percent reduction, mostly on shoulder seasons where temperature changes exceed the PCM transition range. The analysis shows that PCM is best performed when transition temperatures are chosen in accordance with the local climate patterns and internal temperature set points.

The electrochromic glazing systems showed a tremendous effect in cooling energy requirements and visual comforts. In structures with large glazing surfaces, active management of the solar heat gain coefficient led to a cooling load savings of 25-40 percent of that of a high-performance glazing with low dynasty. The automatic tinting to the sun radiation ensured that excessive amount of heat could not enter the rooms during peak time and ensured that daylight could be available during cloudy weather and morning and evening. Combination with occupancy sensors and building automation systems allowed zone-based control to strike a balance between energy use and occupant preferences towards view and natural light. The analysis showed that the electrochromic glazing is most beneficial on east and west facades where the penetration of the sun is low and poses a major challenge in thermal and visual effects. In the north hemisphere, southern facades work in favor during the summer but should be effectively controlled in winter to prevent negative effects of blocking the desirable solar heat gain.

Self-healing concrete that includes a bacterial activation mechanism and encapsulated healing agents had the ability to extend projected service life by 30-50 percent than conventional concrete that had to undergo periodic repair and protection treatments. The crack repair ability is autonomous which minimizes water infiltration, chloride penetration and carbonation which undermine structural integrity and durability. The analysis of the lifecycle shows that the initial cost, in terms of premiums of material, is 15-30; however, the maintenance costs are lowered, and the replacement cycle is prolonged leading to a 18-25 cost saving of the lifecycle. The embodied energy analysis shows that long life span saves a lot of energy on the environment since the amount of energy used in demolition of concrete, production, and placement in a cycle is also very high.

Passive design methods were also very performance in all climate zones when adjusted to the local conditions. Best building orientation was determined by latitude and climate, but usually used longer building axes that had east-west orientation to reduce heat gain on primary facades during the summer and maximize the sun exposure in the winter. According to the simulation outcomes, total energy consumption can be decreased by 8-15 percent when the orientation is introduced correctly so that the placement is arbitrary.

Optimization of window to wall ratio indicated patterns unique to climate. There were hot climates, and the ratios of windows on east and west facades were 20-30% to reduce cooling loads, and to give

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sufficient daylighting. South facades were capable of having a greater ratio of 35-45% with the correct external shading devices to keep out the high-angle of the summer sun, and allow the low-angle of the winter sun. South-facing glazing ratios up to 50-60% offered the net heating advantages of during cold climates when a high-performance low-emissivity glazing as well as a thermal break had been used. North facades in every climatic condition worked best when glazed half to a third or 15-25% in order to minimize heat loss and still allow the view and use secondary daylight.

Natural ventilation techniques showed success in saving cooling energy in both temperate and hot-dry climates where one can use out-of-doors conditions to ensure comfort in indoors in extensive parts of the year. Combined approaches of cross-ventilation and operable windows on alternative facades minimized mechanical cooling by 30-50% with suitable thermal mass to reduce temperature variability. Vertical shafts or atria stack ventilation allowed good air circulation in lower floor plans where cross-ventilation is limited. Natural ventilation performance was constrained by the elevated moisture content in the outdoors, which in hot-humid climates, however, offered helpful air movement in the morning and evening hours. In cold climates, the natural ventilation was mainly applied to assist in the air quality in mild shoulder seasons.

The research studies which aimed to optimize the use of thermal mass revealed that concrete floor slabs and interior masonry walls are effective in moderating the changes in indoor temperatures when correctly exposed to indoor spaces. Thermal mass slowed peak temperatures in buildings with high internal heat gains of occupants and equipment by 3-5 hours and minimized temperature swings by 2-4 degrees Celsius. This was improved using the thermal storage effect strategies that combine with nighttime ventilation strategies used to flush out stored heat in the mass. The discussion indicated that the effectiveness of thermal mass construction is very reliant on the exposure of surface area and the carpeted or ceiled ceiling scenario considerably lowered the performance.

Optimization of daylighting produced sufficient quantities of illuminance in most areas of occupied floor, 75-90% with a mixture of clerestory windows, light shelves, and high-reflectance interior surfaces. The daylight autonomy study revealed that 60-80 percent of occupied daylight in the perimeter areas that expanded 15-20 feet along the facades could be without electric lighting. Photosensor-based dimming controls with natural daylighting strategies also cut the energy use on lighting by 50-70% over fully electric lighting schemes.

Climate responsive design synthesis was a synthesis that applied several passive strategies into coherent design systems tailored to each climate zone. In humid hot climates, the most appropriate strategy was based on reduced glazing, massive use of shading devices, natural ventilation as a quality of air, and dehumidification strategies. Hot-dry weather was advantageous to thermal inertia, evaporative cooling, night ventilation, and courtyards, which form safe microclimates. Balanced glazing, thermal mass, natural ventilation and seasonal responsiveness were found to be the most effective in temperate climates. Cold weather gave more importance on south-facing solar gain, thermal mass, high insulation and reduced intrusion.

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The complete performance simulation using smart materials with the optimization of passive strategies showed the total energy savings of 65-78% in comparison with traditional baseline buildings. The combination was more effective than the single strategies that were used separately, which revealed synergistic effects between envelope performance, thermal storage, solar control, and natural ventilation. The review indicated that to achieve net-zero performance regarding energy performance passive strategies and smart materials needed to be supplemented with a small amount of renewable energy production, 40-60 kilowatt-hours per square meter per year of photovoltaic arrays.

Economic studies showed that the integrated method has a premium cost of construction of 8-18% relative to the conventional construction. The savings in operation energy however lead to easy payback in 10-18 years based on the cost of energy and climatic conditions in the locality. The net savings of the lifecycle cost analysis in 50-year lifespans of both the building as shown give a saving of 25-40 percent in relation to normal construction in the case of energy cost escalation.

The results are consistent with the past studies showing that the performance of net-zero energy buildings can be attained in a variety of climatic regions through the integrated design strategies [42, 43]. The findings are an expansion of prior knowledge because they quantify the performance benefits of any given material technologies and how they interact with passive strategies in different environmental conditions. The review proves that, design methods that are context-specific are more productive than prescriptive criteria or general templates of designs [44, 45].

The identified challenges in implementation are the unavailability of some of the advanced materials in particular markets, the existence of specialized design knowledge, the more detailed construction description, and the education of the occupants on the passive system functioning. These obstacles imply that general implementation will demand simultaneous improvements in materials production, licensing and training of professionals, construction processes, and building commissioning procedures [46, 47].

The study has shown that it is technically possible to reach the goal of net-zero energy in urban architecture through the use of the existing technologies and design experience. The combination of smart materials and passive solutions offers numerous options of reducing dramatically the energy needs, allowing to scale the renewable energy systems and make them economically feasible. The climate-responsive approach acknowledges that the best solutions are location-specific, and thus should be analyzed and tailored to a particular area, and not offered in a universal form [48].

Conclusions

This study confirms that the integration of smart materials and passive design solutions offers practical solutions to attaining the goals of net-zero energy performance of urban buildings. The holistic overview demonstrates that the strategic integration of phase-change materials, electrochromic glazing, self-healing concrete, and climate-responsive passive design can help cut down building energy consumption at 60-75% of the usual construction processes. Such dramatic demand reduction allows practical implementation of renewable energy systems of scales needed to apply to unmet energy needs, and net-zero energy targets have become technically and economically feasible.

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The use of phase-change materials in the building envelopes proves to be effective in controlling thermal loads and peak energy demand, by means of latent heat storage mechanisms through which the thermal loads in building envelopes are moderated. Optimal location-specific climate patterns and interior comfort needs can be met when PCM transition temperatures are matched to the local climate patterns and interior comfort needs. Electrochromic glazing systems offer an active solar regulation system that strikes a balance between thermal performance, day lighting and comfort of occupants by automatically adjusting to environmental conditions. Self-healing concrete increases the structural life of the structure and decreases lifecycle environmental impacts caused by self-healing in terms of repair of damages.

Passive design solutions such as optimum building orientation, size, and placement of the windows, natural ventilation, utilization of thermal mass, and optimization of daylighting play an important role in reducing the energy demand when adequately tailored to the climate and the purpose of the building. Passive strategies have a much greater effectiveness in different climatic zones, which supports the idea that design methods should be developed according to the specificities of the context, and no universal rules are applicable.

Evidence-based design decisions can be made with the help of Building Information Modeling platforms and integrated energy simulation tools that allow predicting the design performance accurately at the conceptual and detailed design stages. These digital tools make it possible to identify the synergies of various strategies and optimize design-related details that have a significant effect on the overall performance.

According to the economic analysis, the cost savings associated with net-zero energy buildings include the cost-premium of construction between 8-18 percent of the cost of a building and high lifetime cost savings due to low operational energy consumption. The brevity of payback periods between 10-18 years is good considering the 50-75 years of the building lifespan as a good indicator of economic feasibility in the long term and its environmental impact.

The attainment of net-zero energy performance in the urban architecture deals with some important environmental issues such as mitigation of climate change, conservation of resources, and sustainable development. Architectural constructions developed with the help of integrated designs, combining smart materials and passive constructions not only reduce the energy usage and carbon emissions but also improve the comfort of the occupants, indoor environmental conditions, and quality of architectural designs. The climate-responsive design philosophy advocates the idea of buildings that can interact with natural environmental forces instead of solely riding on the assistance of mechanical systems to achieve greater resiliency and flexibility.

The mass implementation of the principles of net-zero energy design presupposes the simultaneous developments in the following areas such as the production and supply of materials, the professional education and training, the construction practice and quality management, building codes and standards, and the awareness and participation of the occupants. Technical knowledge and material technologies that can achieve net-zero energy performance are already available, yet the institutional and market barriers to this technology exist.

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Future research areas encompass long-term performance observations of net-zero energy buildings, which confirm the forecasts of simulations and reveal the opportunities of optimizing the operations, the creation of cheaper smart materials that can be introduced into the mass market, exploration of retrofit approaches that can be used to apply the principles of the net-zero energy to the current building stock, and the study of scalability issues in high-density urban environments when site limitations restrict the potential of renewable energy generation.

The convergence of intelligent materials and passive design approaches signifies the radical departure of architectural practice of buildings as passive and closed systems in their environment but dynamic systems which responsively act and interact with the environment. This paradigm will allow architecture to make a significant contribution to mitigating climate change and improving the comfort and well-being of people. The findings made in this study indicate that net-zero energy performance can be realized through the use of currently available technologies and knowledge, which is an easy way to go in the process of achieving sustainable urban development.

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