A Review Paper on Bridging Technology and Ecology: Review on Renewable Energy Systems and Green Construction Materials

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Abstract - The idea of sustainable architecture has transformed from a specialized concept into a fundamental aspect of modern urban planning, especially in Maharashtra, where accelerated urbanization has amplified environmental pressures. This study evaluates the design performance and environmental impact of two notable GRIHA-rated projects—Raheja Vistas T12 & T13 in Pune and Raj Bhavan, Nagpur Division—which serve as models of green architecture in India. Both structures emphasize energy optimization, water efficiency, renewable energy utilization, and occupant well-being across residential and institutional contexts.
Raheja Vistas, developed by K. Raheja Corp, achieves approximately 40.28% reduction in energy use and 33.72% savings in water through the implementation of high-performance materials, effective daylight utilization, low-flow sanitary fixtures, and waste-to-compost management systems. Conversely, the Raj Bhavan retrofitting project incorporates a 4 kWp solar photovoltaic installation, enabling a 32.85% renewable energy contribution and a 40.79% decrease in water usage while maintaining the site's architectural heritage.
These case studies highlight Maharashtra's proactive role in advancing India's green building movement, guided by IGBC and GRIHA frameworks. Their achievements demonstrate how policy support, design innovation, and interdisciplinary collaboration can make sustainability not only an ecological necessity but also a driver of economic strength, improved quality of life, and progress toward the nation's long-term net-zero carbon objectives.

***Key Words*:** Sustainable Architecture, Green Building, Urban Development, Maharashtra, Environmental Challenges, GRIHA, IGBC, Energy Efficiency, Water Conservation, Renewable Energy, Occupant Comfort.

1.INTRODUCTION

1.1 General:

Maharashtra's dedication to sustainable development is evident through its extensive green building initiatives and regulations designed to transform the construction industry into an example of environmental responsibility. The state has introduced several frameworks, including the Maharashtra Green Building Policy, which provides incentives such as rebates on development charges and property taxes for projects certified under IGBC and GRIHA. In addition, the Energy Conservation Building Code (ECBC) Rules 2025 draft proposes stricter energy performance standards for commercial buildings, focusing on efficient envelope design, HVAC optimization, advanced lighting systems, and renewable energy integration. These policy measures reflect Maharashtra's commitment to aligning with India's national climate goals, reducing urban environmental stress, and promoting sustainable resource utilization.

The adoption of green buildings in major cities such as Pune, Nagpur, and Mumbai—where residential and institutional projects serve as successful models—illustrates Maharashtra's leading role in large-scale sustainability implementation. The state's green infrastructure strategy effectively combines technological innovation with policy support to foster energy-efficient, water-conscious, and health-promoting built environments. Projects like Raheja Vistas and Raj Bhavan exemplify that environmentally responsible designs can be both economically feasible and socially advantageous. These developments exhibit measurable reductions in energy and water consumption, the use of renewable energy systems, and sustainable building materials while improving indoor environmental quality.

As Maharashtra continues to urbanize rapidly, replicating such success stories is essential to maintaining ecological balance amid development. The state's proactive stance positions it as a benchmark in integrating sustainable construction norms into mainstream infrastructure planning. This approach contributes to India's ambition of achieving net-zero emissions by 2070 and nurturing resilient, livable urban spaces.

Green buildings are designed to minimize environmental degradation while enhancing the relationship between humans and nature. They are constructed using eco-friendly and resource-efficient methods across their entire life cycle—from site selection and design to construction, operation, maintenance, and eventual demolition. This methodology aims to reduce the negative impact of buildings on the environment and human health by ensuring efficient use of energy, water, and materials while minimizing waste, pollution, and ecological damage. Such buildings often utilize sustainable construction materials and modern energy systems that lower carbon emissions and improve indoor living conditions.

The primary objective of green building practices is to harmonize sustainability with the built environment, promoting responsible construction practices that support a higher quality of life. By emphasizing energy and water conservation, waste reduction, and pollution control, green building design ensures both environmental protection and public well-being. A notable aspect of sustainable construction is the reuse of salvaged materials—such as broken tiles, bricks, concrete, or timber—from demolition sites. This not only supports waste management and cost reduction but also encourages a circular economy within the construction sector.

Green construction also emphasizes improving indoor environmental quality. Proper building orientation—preferably toward the east—combined with larger openings or glazed façades allows for greater natural light and ventilation, reducing dependence on artificial lighting and cooling systems. Incorporating renewable energy sources like solar photovoltaic panels, passive and active solar designs, and vegetated features such as rooftop gardens and green walls further enhances sustainability. These elements strengthen the connection between people and nature while reducing rainwater runoff and supporting efficient water management.

Ultimately, green buildings embody a holistic approach to construction that addresses environmental concerns while promoting human health, comfort, and ecological balance. Through intelligent site selection, efficient system design, and renewable energy integration, Maharashtra's green building movement demonstrates how sustainable architecture can lead to a cleaner, healthier, and more resilient urban future.

1.2 Seven Green Building Components:

- Energy-Efficient Windows: It keeps the house temperature stable and is the primary source of heat loss. There are many different styles and designs within budget in the market.
- Green Roof: They are well-liked because they lessen heat loss via the roof and aid in home insulation. In addition to providing room for flora and fauna, it also lowers storm water runoff.
- Solar Power: Solar power is a renewable energy source that heats and cools a home and provides electricity. It is affordable and reduces carbon footprints.
- Water Conservation: The most straightforward and affordable methods of conserving water include gathering rainwater in barrels and buckets, establishing rainwater harvesting systems, using clever scraping techniques, and creating water-conserving landscaping.
- Recycling: Recycling is an excellent method of reducing the garbage produced in the household. It is a beautiful technique to recycle stuff as well.

1.3 Objectives:

1. To evaluate the environmental benefits of GRIHA-rated projects in Maharashtra.
2. To analyze design interventions that achieve measurable reductions in energy and water demand.
3. To establish frameworks and best practices for replicating similar projects statewide.
4. To analyze challenges and limitations faced during the execution of green projects and suggest practical solutions for overcoming them.
5. To compare environmental and operational performance between residential and institutional building typologies in Maharashtra.

1.4 Concept of Sustainable Development:

Sustainable development seeks to achieve a balance between economic growth, social equity, and environmental protection. It emphasizes using natural resources responsibly to minimize environmental damage and lessen the effects of climate change. By promoting equitable access to opportunities such as education, healthcare, and employment, it ensures that the benefits of progress are shared across all sections of society. Furthermore, sustainable development fosters innovation and supports the adoption of eco-friendly technologies that create new industries and employment opportunities while reducing carbon emissions. Prioritizing renewable energy sources and sustainable practices contributes to cleaner air, safer water, and the preservation of ecosystems.

In the construction sector, sustainable development plays a crucial role in addressing the rising demand for infrastructure while minimizing environmental harm. The industry is a major consumer of non-renewable resources such as coal, fossil fuels, and minerals, which significantly contribute to pollution and carbon emissions. Transitioning to renewable energy sources like solar, wind, and hydropower can reduce this dependency and promote long-term resource conservation. Utilizing recyclable materials and adopting energy-efficient building techniques can help the industry reduce its environmental footprint. Green building practices—such as optimizing energy performance, improving water efficiency, and enhancing indoor environmental quality—form the foundation of sustainable construction. Ultimately, integrating these strategies ensures that development remains both environmentally responsible and socially beneficial, paving the way for a resilient and sustainable future.

Fig no 1 Green Building Sustainablity

2. LITERATURE REVIEW

1. Usama Hamed Issa et.al (2025) : This Paper analysed Green building (GB) projects in the Middle East encounter multiple sources of waste that emerge during both the design and construction phases. These factors significantly influence the key goals of GB projects, namely economic efficiency, environmental sustainability, and social responsibility. The purpose of this research is to identify and analyze the major causes of waste in GB projects and assess their impact on these three primary objectives. A total of forty-five waste causes were identified and categorized into five major groups: (G01) green materials, (G02) green building design, (G03) sustainable site management, (G04) green building technologies, and (G05) green building stakeholders.

Data were collected through comprehensive field surveys, which included semi-structured interviews and brainstorming sessions with experts and practitioners. Each identified cause of waste was evaluated based on its likelihood of occurrence and its level of influence on the economic, environmental, and social dimensions of project performance. The severity of waste was then determined by combining the probability and impact scores. The study also utilized Spearman's correlation analysis to examine the interrelationships among various waste indices. Overall, the research provides valuable insights into how waste generation in GB projects can be minimized through effective design, technology integration, and stakeholder collaboration, ultimately improving sustainability outcomes across all project phases.

2. Vinayak Pavate et.al (2024) : In today's rapidly developing world, the expansion of infrastructure serves as a key indicator of a nation's progress. However, such growth must be harmonized with environmental preservation to safeguard the well-being of humans and all living organisms. The construction industry, while being a major contributor to economic development, also remains one of the largest sources of environmental degradation, responsible for nearly 40% of global air pollution. The manufacturing and transportation of building materials—particularly cement and steel—are significant contributors to this issue. These processes release large volumes of carbon dioxide (CO_2), a greenhouse gas that intensifies global warming and disrupts atmospheric balance. Cement production alone is estimated to generate 8–10% of total anthropogenic CO_2 emissions, while steel manufacturing adds another 5–10%. Such emissions not only harm ecosystems but also deteriorate human health and living conditions.Although completely eliminating greenhouse gas emissions is difficult, adopting sustainable construction and eco-friendly design strategies offers an effective path toward reduction. The primary goal of Green Building and Energy-Efficient Design is to create environmentally responsible and energy-conscious structures that strengthen the relationship between humans and nature while minimizing pollution for future generations. Green buildings efficiently utilize energy and natural resources, reduce waste generation, and provide healthier indoor environments. By emphasizing renewable materials, advanced energy-saving technologies, and innovative architectural practices, these buildings significantly reduce carbon footprints, mitigate climate change, and support ecological balance.

3. Yunpeng Hu et.al (2025) : In the context of the growing global challenge of climate change, environmental design and thermal management have become crucial areas of research. This study utilizes the immersive and interactive capabilities of Virtual Reality (VR) technology to develop an integrated framework for green building design and thermal energy optimization. By examining the requirements of sustainable architecture and assessing the potential of VR applications in building design, a comprehensive thermal management system was established that combines sensor networks, data analysis, and intelligent control mechanisms.

The research explores in depth the potential of VR in enhancing green building performance, focusing on creating an intelligent, high-efficiency system that improves environmental design quality and optimizes thermal energy use to achieve energy conservation objectives. During the study, the diverse demands of green building design—such as ecological sustainability, occupant comfort, and cost-effectiveness—were thoroughly analyzed. The distinct advantages of VR, including immersive visualization, real-time interaction, and dynamic simulation, were identified as key tools for architectural innovation. Building on these insights, an integrated system was developed that combines environmental modeling, thermal management, and predictive analytics by incorporating advanced technologies such as VR, sensors, data acquisition and processing, and automated control systems.

3. METHODOLOGY :

3.1 Data Collection

The data collection process for this research, focused on successful green building projects in Maharashtra, was systematically structured to obtain both quantitative and qualitative information. The study concentrated on the sustainable design strategies, construction techniques, and operational performance of two selected case studies—Raheja Vistas in Pune and Raj Bhavan in Nagpur.

3.1.1 Primary Data Collection

Site Visits and Observations:
Several on-site visits were carried out at both project locations to directly examine their architectural configurations, observe sustainable features in operation, and assess site-specific environmental conditions. Photographs, schematic layouts, and relevant visual records were obtained to support detailed analysis and evaluation.

3.1.2 Secondary Data Collection

- Project Documentation Review:
  Architectural drawings, technical specifications, equipment data sheets, and sustainability certification documents (such as GRIHA scorecards) were examined to extract essential technical information and confirm compliance with certification criteria.

- Government and Institutional Reports:
  Official reports, policy documents, and regulatory frameworks related to green building promotion in Maharashtra were reviewed using credible government and institutional sources.

- Literature and Case Study Analysis:
  Academic journals, technical studies, and professional publications were analyzed to establish a contextual foundation and to compare existing findings with the outcomes of the present research.

4. GREEN BUILDING AS A RENEWABLE ENERGY:

4.1 Overview of Renewable Energies in the Building Sector:

Renewable energy, harnessed from naturally replenishing sources, offers a cleaner and more sustainable alternative to conventional fossil fuels (Dey et al., 2022). In the context of the building sector, it refers to the incorporation of eco-friendly energy systems—such as solar, wind, geothermal, and biomass—throughout the entire life cycle of a building, including its design, construction, operation, and maintenance. This integration minimizes dependence on non-renewable energy sources, supports environmental protection, and contributes to climate change mitigation.The origins of renewable energy use in architecture can be traced back to early applications of passive solar design, which utilized building orientation, daylight, and natural ventilation to optimize thermal comfort (Gong et al., 2022; Ionescu et al., 2015). With growing awareness of environmental sustainability, renewable energy technologies in modern construction have evolved rapidly, driving innovation and efficiency. The selection and application of renewable energy in buildings primarily depend on the building's energy requirements, geographical conditions, and the nature of available resources. Among the diverse renewable energy options, solar, wind, hydro, geothermal, biomass, tidal, and hydrogen energy stand out as the most developed and widely adopted technologies in the global renewable energy landscape.

Types of Renewable Energy Used in Buildings:

1. Solar Energy
2. Wind Energy
3. Geothermal Energy
4. Biomass Energy

1. Solar Energy

Solar energy is one of the most abundant and widely utilized sources of renewable energy, harnessed by converting the sun's radiant power into usable electricity or heat. It is regarded as a limitless and eco-friendly energy source, making it a leading contender for replacing fossil fuels in the future. According to Aldhshan et al. (2021), solar energy is a sustainable power source that generates electricity through photovoltaic (PV) systems. In building applications, solar technology primarily captures solar radiation and thermal energy through two major approaches: photovoltaic systems and solar thermal systems. These can be further categorized as active and passive solar systems. Active systems include solar panels, PV modules, and solar water heaters that directly convert sunlight into energy. In contrast, passive systems optimize building orientation, air movement, and thermal storage to naturally regulate indoor temperatures without mechanical devices. Together, these technologies make solar energy one of the most practical and adaptable renewable solutions for modern buildings.

2. Wind Energy

Wind energy has emerged as a rapidly expanding renewable resource, especially with advancements in offshore wind technologies that have broadened its application in the building sector (Zhang et al., 2023). A wind energy system typically comprises turbines that transform wind's kinetic energy into mechanical or electrical power using vortex-based mechanisms. Similar to solar energy, wind systems are generally classified as active or passive, depending on turbine size and operational principles. Active systems rely on motor-driven rotation, whereas passive systems rotate naturally with the direction of the wind (Palraj and Rajamanickam, 2020). Common building-integrated applications include wind power generation, natural ventilation systems, wind tunnels for performance testing, and aerodynamic design enhancements (Deymi-Dashtebayaz et al., 2022; Peng et al., 2020b).

Studies reveal that wind energy helps significantly cut carbon emissions and reduce dependency on non-renewable fuels. By 2017, global wind utilization had prevented approximately 600 million tons of greenhouse gas emissions (Yousefi et al., 2019). Building-integrated wind systems can generate nearly 15% of total energy requirements on-site (Kwok and Hu, 2023). Incorporating natural ventilation techniques allows indoor-outdoor airflow, reducing reliance on air conditioning and lowering energy consumption. In this regard, Wang et al. (2021a) developed an innovative turbine damper ventilator that minimizes unwanted exhaust air while maintaining comfortable indoor air quality and energy efficiency.

3. Geothermal Energy

Geothermal energy harnesses the Earth's internal heat to produce sustainable thermal energy (Osman et al., 2023). This constant heat flow within the planet's crust, combined with groundwater circulation, creates a renewable energy resource that operates continuously regardless of weather or time of day (Palmero-Marrero et al., 2020). Unlike solar and wind systems, which are primarily used for electricity generation, geothermal systems are mostly applied for heating and cooling purposes. When combined with other renewable sources such as solar, geothermal energy enhances industrial efficiency and contributes to economic development and job creation. Based on depth, geothermal systems are classified as shallow, intermediate, or deep, though no universal classification exists (Romanov and Leiss, 2022b).Applications include power generation, direct heating, and heat extraction using ground-source heat pumps. Compared to conventional systems, geothermal solutions improve energy efficiency, lower operational costs, and significantly reduce greenhouse gas emissions. D'Agostino et al. (2022b) demonstrated through simulation modeling that geothermal heat pumps and geo-aerothermal exchangers can cut primary energy demand and CO_2 emissions, advancing net-zero energy goals. These systems also operate quietly and require minimal land, making them ideal for space-limited urban areas (Shah et al., 2022). Studies estimate geothermal plants require only 7.5 m^2 per MW annually—less than most other energy technologies (Tester et al., 2021).However, installation costs remain high due to drilling and subsurface components (Hu et al., 2021; Lizana et al., 2018). Geological conditions greatly influence performance, as unsuitable subsurface structures can increase risks and costs (Chen and Feng, 2020). Despite these challenges, geothermal energy remains an efficient, low-emission solution offering design flexibility for sustainable buildings.

4. Biomass Energy

Biomass energy originates from organic matter derived from plants, animals, and microorganisms, which can be converted into energy through combustion, gasification, or anaerobic digestion (Yang et al., 2022a). It represents one of humanity's oldest renewable energy sources. In the building sector, biomass materials are utilized in both structural and non-structural forms to reduce fossil fuel dependency and minimize carbon emissions. Biomass primarily relies on resources such as wood, agricultural residues, plant fibers, and organic wastes. Techniques like biogas production and direct combustion are commonly employed to meet energy requirements in buildings. Moreover, waste materials—including construction debris and animal manure—can be used to generate electricity through biomass power plants (Khan and Al-Ghamdi, 2021).For instance, Rahman et al. (2015) studied a biomass-based 115 kW power plant capable of meeting the energy demand of an entire residential building. Biomass can thus serve multiple building functions, including biogas generation, biofuel heating, and electricity production, contributing to sustainable and carbon-neutral infrastructure.

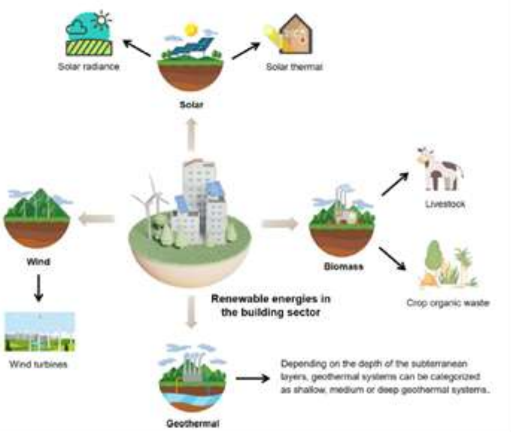

Fig no 2 Types and sources of Renewable energy

4.2 GREEN MATERIALS:

Over the past few decades, extensive research has been conducted to minimize the energy demand during the operational phase of buildings. This includes reducing the energy required for maintaining indoor thermal comfort (heating and cooling), ensuring proper ventilation, and providing hot water for appliances and lighting systems. As a result, many buildings have achieved improved energy performance throughout their service life by effectively integrating advanced materials and efficient construction technologies.The ongoing focus on utilizing renewable energy sources has accelerated the development of the concept of Zero Energy Buildings (ZEBs). This concept refers to achieving an annual energy balance in which the total energy consumed during building operation is offset by energy generated from renewable resources such as solar or wind power—illustrated by examples like solar-powered houses.In a broader and more practical sense, green building (GB) materials can be defined as those that:

- Maintain sustainability throughout their entire life cycle, measurable through Life Cycle Assessment (LCA) using a “cradle-to-grave” approach; and

- Are non-toxic and safe for occupants, meaning they do not release pollutants that compromise Indoor Air Quality (IAQ). Such materials should not emit harmful substances like volatile organic compounds, radon, or hazardous fibers, nor encourage biological growth or surface dampness that may create unhealthy indoor environments.Both sustainability and occupant health considerations must be equally prioritized when evaluating and selecting materials for green building applications.

Examples of Green Materials

1. Quarry Dust

Quarry dust is a by-product generated during the crushing, screening, and blasting of rocks for aggregate production. It consists of fine particles generally smaller than 4.75 mm and has an angular, rough texture that enhances interlocking among particles, thereby improving the strength of the resulting concrete. When used as a partial replacement for sand in concrete, quarry dust increases resistance to acids and sulphates while lowering permeability compared to conventional Portland cement concrete. However, in some cases, additional cement may be required to maintain adequate workability within acceptable limits.

2. Fly Ash

Fly ash is a fine, powdery residue produced from the combustion of coal in thermal power plants. It is typically collected from flue gases through electrostatic precipitators. There are two main types—fly ash (fine particles) and bottom ash (coarser residue). Its composition varies depending on the source of coal but generally contains silicon dioxide (SiO_2) and calcium oxide (CaO). Fly ash can partially replace Portland cement in concrete, improving strength, durability, and workability while reducing water demand. When used appropriately (up to 80% replacement with activators), it minimizes the heat of hydration and enhances long-term performance.

3. Masonry and Concrete Waste

Recycled concrete and masonry waste are processed into coarse and fine aggregates that can be reused in new construction, particularly in road base layers and non-structural applications. These materials often contain crushed brick, stone, or gravel fragments. While recycled aggregates reduce the demand for virgin materials, their excess fines can influence workability, surface finish, and the rate of bleeding in concrete. Proper grading and proportioning can mitigate these challenges, making them an effective sustainable alternative.

4. Silica Fume

Silica fume is a by-product of industrial silicon and ferrosilicon alloy production. Due to its extremely fine particle size, it poses air pollution risks if not managed properly. When incorporated into concrete at 5–15% of the cement content, silica fume enhances strength, density, and durability while lowering permeability. It reacts rapidly with calcium hydroxide to form additional calcium silicate hydrate (C–S–H) gel, improving the microstructure of the mix. However, using more than 20% may adversely affect workability and overall concrete performance.

5. Marble Waste

Marble waste, primarily generated as fine powder during cutting and polishing operations, presents a significant disposal concern for the stone industry. Nevertheless, this waste can be effectively reused in concrete as a filler material, enhancing properties like hardness and surface finish. Its inclusion in suitable proportions reduces environmental pollution while improving sustainability in construction.

6. Crushed Glass

Glass is a hard, transparent, and brittle inorganic material primarily composed of silica (SiO_2) with small amounts of aluminum oxide (Al_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and sodium oxide (Na_2O). When crushed, glass can be incorporated into concrete as coarse aggregate, fine aggregate, or powder. The chemical reaction between glass particles and cement forms calcium silicate hydrate, contributing to pozzolanic activity. Although excessive glass content may reduce compressive strength due to weak bonding, using finely ground glass improves workability and reduces shrinkage in the concrete matrix.

7. Polyethylene Terephthalate (PET)
Polyethylene terephthalate (PET) is a polyester-based polymer made from ethylene glycol and terephthalic acid. When processed and incorporated into concrete as lightweight aggregates, PET reduces environmental waste and enhances ductility. Studies have shown that concrete with PET aggregates exhibits densities ranging from 1940–2260 kg/m³ and improved crack resistance due to enhanced flexibility. However, higher PET content (above 15%) may reduce compressive strength, elastic modulus, and specific gravity.

8. Ceramic and Tile Waste
Ceramic and tile waste originate from manufacturing defects, breakage during transport, or demolition of old structures. These non-metallic, inorganic materials can be crushed and reused in concrete as coarse or fine aggregates. Research indicates that substituting 10–50% of natural aggregates with ceramic waste can enhance compressive strength and reduce waste disposal problems. When porcelain or sanitary ceramic waste is used at moderate replacement levels (5–20%), it improves mechanical performance after 28 days of curing, making it an effective sustainable substitute.

5. CONCLUSIONS

Integration of Sustainability Principles:
The study emphasizes that sustainable development in the construction sector is essential to balance environmental protection, economic growth, and social well-being, particularly through the adoption of renewable and eco-friendly materials.

Insights from Literature Review:
Previous research highlights that using alternative materials such as fly ash, quarry dust, and recycled aggregates can significantly reduce carbon emissions, conserve natural resources, and improve concrete durability.

Methodological Understanding:
The analysis and comparison of material properties, performance tests, and replacement ratios provide a systematic approach to evaluating the suitability of green materials for practical construction applications.

Effectiveness of Renewable and Green Materials:
Materials like silica fume, marble waste, PET, and ceramic waste demonstrate strong potential in enhancing strength, workability, and sustainability while minimizing environmental pollution and industrial waste disposal issues.

Future Scope and Impact:
The widespread implementation of renewable and green materials can transform conventional construction practices, promoting a low-carbon, resource-efficient, and resilient built environment aligned with India’s net-zero and sustainable development goals.

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