

Design and Analysis of a Net zero Residential Building

Mr. Aniket Garud¹, Mr. Aryan Shikhare², Mr. Rushikesh Suryawanshi³, Mrs. Bhagyashri Deshmukh⁴

^{1,2,3}Research Student, Department of Civil Engineering, Dr. Daulatrao Aher College of Engineering, Karad, Maharashtra, India.

⁴Project Guide, Department of Civil Engineering, Dr. Daulatrao Aher College of Engineering, Karad, Maharashtra, India.

ABSTRACT-This project presents the comprehensive design and analysis of a holistic net zero residential bungalows situated in the hot and semi-arid climate. The primary objective is to conceptualize a climate responsive structure that entirely neutralizes its environmental footprint across energy water and waste streams. Architectural drafting and spatial modeling are executed using AutoCAD and SketchUp to aggressively optimize building geometry orientation and passive solar benefits. By prioritizing high thermal mass materials strategic fenestration and natural cross ventilation the baseline cooling load is significantly minimized. To achieve net zero energy status a mathematically sized grid tied rooftop solar photovoltaic system is integrated to offset the calculated annual energy consumption. Furthermore the project establishes a closed loop hydrological cycle by combining high efficiency plumbing fixtures with a comprehensive rainwater harvesting network and an on site greywater reclamation system for secondary utility. Addressing the net zero waste frameworks the design enforces a circular economy approach featuring strict source segregation and the biological processing of organic waste via an aerobic composter or biogas digester. Ultimately this study demonstrates the technical viability of a scalable localized blueprint for sustainable residential architecture that balances modern living standards with rigorous environmental responsibility in western Maharashtra.

Key Words: Net Zero Energy Building, Passive Cooling Strategies, Rainwater Harvesting, Circular Economy, Sustainable Residential Design, Bioremediation

1. INTRODUCTION

The global construction and building operations sector is responsible for a significant proportion of total global energy consumption and greenhouse gas (GHG) emissions. As rapid urbanization accelerates, particularly in developing nations like India, the demand for residential housing is expanding exponentially. Conventional residential construction relies heavily on energy intensive active systems for cooling and heating, while simultaneously imposing massive burdens on municipal water supplies and waste management infrastructure. In response to the escalating climate crisis, the civil engineering and architectural paradigms are shifting aggressively toward sustainable construction methodologies,

moving from standard green buildings to holistic, self-sustaining structures.

1.1 The Concept of Holistic Net Zero Buildings

While the traditional definition of a Net Zero Energy Building (NZE) focuses solely on energy, a holistic approach expands this philosophy to encompass all critical resource streams.

- **Net Zero Energy:** Utilizing passive architectural design to minimize demand, optimizing efficiency with high performance appliances, and offsetting remaining requirements using on site renewable generation like Solar Photovoltaic (PV) systems.
- **Net Zero Water:** Establishing a closed-loop hydrological cycle through high efficiency fixtures, rainwater harvesting, and on site greywater treatment for secondary applications.
- **Net Zero Waste:** Transitioning to a circular economy via meticulous source segregation and the on-site biological processing of organic waste.

1.2 Objectives of the Study

The primary objective of this project is to conceptualize, design, and analyze a climate responsive, net zero bungalow. The specific goals include:

- Developing an architectural plan and 3D spatial model using AutoCAD and SketchUp to optimize orientation and passive solar benefits.
- Minimizing the energy demand by integrating passive cooling techniques and strategic window to wall ratios (WWR).
- Designing a grid tied rooftop Solar PV system sized to achieve Net Zero Energy status.
- Formulating an integrated water management system and an on site operational waste management strategy to neutralize the building's environmental footprint.

2. METHODOLOGY

The design and analysis of the proposed bungalow are governed by the "Trias Energetica" concept, which dictates

that energy generation should only occur after all measures to reduce and optimize consumption have been exhausted.

2.1 Passive Design and Energy Optimization

The initial design phase focuses on heat avoidance. Architectural drafting is executed using AutoCAD for 2D spatial planning, followed by 3D visualization and shading analysis in SketchUp. The building's geometry is optimized to face North and South, controlling solar radiation through horizontal shading devices. High thermal mass materials, such as thick brickwork, are specified to absorb heat slowly during daytime hours and release it at night, dampening indoor temperature fluctuations. Additionally, the internal layout is configured to align operable windows on opposite walls, facilitating natural cross-ventilation to reduce mechanical cooling loads. Efficiency is further maximized by integrating 100% Light Emitting Diode (LED) fixtures and high efficiency appliances.

2.2 Resource Management Systems Integration

Once the baseline electrical load is minimized, a grid tied rooftop Solar PV system is mathematically scaled to offset the annual consumption. To achieve Net Zero Water, a rainwater harvesting system is designed using the physical catchment equation to capture seasonal monsoon precipitation, augmented by a decentralized greywater

3. LITERATURE REVIEW

The paradigm of Net Zero Energy Buildings (NZEB) has evolved significantly from a theoretical environmental ideal to a heavily regulated and mathematically verifiable engineering standard. Foundational literature by Torcellini et al. [1] and Crawley et al. [2] established the core definitions of zero energy, distinguishing between site, source, and emission boundaries. This established the "Net Zero Site Energy" metric as the most practical framework for residential architecture, a concept further reinforced by the International Energy Agency's global tracking reports [3]-[5].

Transitioning these global definitions to the Indian subcontinent requires stringent adherence to localized climatic and regulatory frameworks. The Bureau of Energy Efficiency's (BEE) Eco Niwas Samhita [6] and the National Building Code of India [7] provide the mathematical boundaries for the Residential Envelope Transmittance Value (RETV) specifically for hot and semi arid climates like Sangli. Rating systems such as SVAGRIHA [8] and IGBC [9] expand this focus, dictating that true residential sustainability must incorporate holistic resource management, a sentiment echoed by overarching reviews on India's net zero movement [10], [11].

A fundamental pillar of achieving these standards is passive architectural design. Extensive studies demonstrate that optimizing building orientation, employing high thermal mass materials, and calculating precise Window-to-Wall Ratios (WWR) can dramatically reduce baseline cooling

loads in arid regions [12]-[15]. Furthermore, the integration of natural cross-ventilation and night-purge cooling has proven highly effective in stabilizing indoor temperatures against harsh daytime solar radiation [16]-[18]. However, predicting the success of these passive interventions requires accurately defining occupant comfort. The Indian Model for Adaptive Comfort (IMAC) [19] revolutionized this approach by proving that occupants in naturally ventilated Indian buildings tolerate a wider, higher temperature band compared to rigid international ASHRAE standards [20], [21]. This adaptive approach significantly lowers simulated mechanical cooling demands.

Once passive loads are minimized, the integration of high-efficiency appliances and active renewable systems becomes viable [22]. Grid tied rooftop Solar Photovoltaics (PV) remain the most scalable solution for residential structures to offset remaining energy consumption, completing the energy loop [23], [24].

Beyond energy, modern literature insists on a holistic "Triple Net Zero" approach, encompassing water and waste. The vulnerability of groundwater in semi-arid regions mandates closed-loop hydrological cycles. Research highlights the critical necessity of spatial rainwater harvesting integration [25], [26] and decentralized greywater reclamation for non-potable secondary use [27]. Similarly, achieving a zero-waste operational footprint requires a shift from linear disposal to a circular economy. Studies advocate for the architectural integration of source segregation spaces and the on-site biological stabilization of organic waste through aerobic composting or micro-biogas digesters [28]-[30].

Together, this integrated approach ensures the residential structure functions not as a resource drain, but as a self-sustaining ecological node.



Fig – Workflow of Research Methodology

4. Net Zero Building Plan



Fig – 3D Drawing Plan

5. DISCUSSION

The proposed designs of a holistic net zero residential bungalow represents a critical intervention in contemporary civil engineering and architectural practices. By transitioning away from conventional, resource heavy construction, this project directly addresses the localized environmental stressors of western Maharashtra. The core philosophy of this model is fundamentally anchored in the 'Trias Energetica' principle, demonstrating that true sustainability is achieved not merely by attaching renewable technologies to a standard building, but by fundamentally altering the building's physical interaction with its surrounding microclimate. It establishes that a residential structure can operate as an autonomous, self-regulating node rather than a passive consumer of municipal resources. Given regions the regions hot and semi-arid climate, the architectural configuration is heavily driven by passive design strategies aimed at mitigating severe thermal heat gain. By optimizing the building's orientation, utilizing locally sourced high thermal mass materials, and strategically calculating the Window to Wall Ratio (WWR), the design inherently suppresses the baseline indoor temperatures. This approach is critical because it proves that incorporating natural cross ventilation and precise shading devices significantly reduces the occupant's reliance on energy intensive mechanical cooling. Consequently, the generating capacity required for the active grid tied rooftop solar photovoltaic system is mathematically minimized, making the pursuit of 'Net Zero Site Energy' both spatially viable on a residential roof and economically feasible for the homeowner.

Beyond energy optimization, the building's response to regional water scarcity forms a cornerstone of its sustainable framework. The vulnerability to uneven monsoon

distribution and seasonal groundwater depletion necessitates a complete departure from linear municipal water reliance. The integration of a closed loop hydrological cycle ensures that seasonal precipitation is effectively captured through a mathematically sized rainwater harvesting infrastructure. Furthermore, the integration of a decentralized greywater reclamation system allows lightly contaminated water to be treated and safely reused for secondary applications such as landscaping and toilet flushing. This aggressive demand mitigation strategy proves that domestic water autonomy can drastically alleviate the escalating strain on municipal aquifers and regional dams. The operational phase of the bungalow further reinforces its holistic zero impact goal by embedding circular economy principles directly into the management of domestic waste. By spatially integrating source segregation within the interior architectural layout, the design actively intercepts the traditional 'take make dispose' trajectory. The localized biological processing of organic waste, utilizing either an aerobic composter or a micro biogas digester, neutralizes the most significant fraction of daily household waste directly on site. This intervention not only yields usable, high value byproducts like natural fertilizer or renewable cooking fuel but also ensures that the property contributes zero organic, methane producing burden to overflowing regional landfills. Ultimately, the technical and spatial analysis of this bungalow establishes a highly replicable blueprint for future residential developments in similar climatic zones. It demonstrates that harmonizing modern, comfortable living standards with rigorous environmental responsibility is an achievable engineering reality. By meticulously balancing passive architectural intelligence with active resource recovery systems, the project validates the feasibility of holistic net zero living, offering a scalable, localized solution to combat urban resource depletion across the Indian subcontinent.

6. CONCLUSION

The comprehensive design and theoretical analysis of the proposed residential bungalow successfully demonstrate the technical and practical viability of achieving a holistic net-zero footprints in a hot and semi-arid climate. By strictly adhering to the 'Trias Energetica' principle, the project proves that aggressive passive architectural interventions such as optimized spatial orientation, the utilization of high thermal mass materials, and strategic fenestration for natural cross ventilation can drastically minimize a building's baseline cooling and lighting demands. This optimization directly enables a mathematically sized, grid-tied rooftop solar photovoltaic system to completely offset the annual operational energy consumption, successfully achieving Net Zero Site Energy status. Furthermore, the localized integration of a closed-loop hydrological cycle, driven by comprehensive rainwater harvesting and decentralized greywater reclamation, successfully neutralizes the building's reliance on vulnerable municipal water grids. Concurrently, the architectural embedding of

source segregation spaces coupled with the on-site biological processing of organic waste ensures that the bungalow achieves a Net Zero Waste operational phase, contributing zero organic burden to regional landfills. Ultimately, this study concludes that transitioning from conventional, linear construction to a self-sustaining, circular residential model is not merely a theoretical ideal but an achievable engineering reality, providing a highly scalable and urgently needed sustainable blueprint for future urban development across Maharashtra and the broader Indian subcontinent.

7. FUTURE SCOPE

While this project successfully establishes the theoretical framework and spatial design for a holistic net zero bungalow, the future scope of this research lies in its physical implementation and empirical validation. Subsequent phases should focus on transitioning these computational models into constructed prototypes to facilitate real-world performance monitoring. The integration of Internet of Things (IoT) based smart metering and environmental sensors would allow for the continuous tracking of actual energy generation, water consumption, and indoor thermal comfort, enabling engineers to compare live operational metrics against the initial simulated baselines. Additionally, future studies must incorporate a comprehensive Life Cycle Cost Analysis (LCCA) and an assessment of embodied carbon to fully quantify the economic payback period and the total environmental impact of the specified construction materials from cradle to grave. Furthermore, there is significant potential to scale this localized, single-family blueprint into larger, multi-story residential complexes or community-level microgrids. By integrating advanced battery energy storage systems (BESS) and artificial intelligence for predictive resource management, future iterations of this design could achieve complete grid independence, thereby accelerating the broader adoption of self-sustaining architecture and informing progressive urban development policies across diverse climatic zones in India.

REFERENCES

- [1] P. Torcellini, S. Pless, M. Deru, and D. Crawley, "Zero Energy Buildings: A Critical Look at the Definition," National Renewable Energy Laboratory (NREL), 2006. Available: <https://www.nrel.gov/docs/fy06osti/39833.pdf>
- [2] D. Crawley, S. Pless, and P. Torcellini, "Getting to Net Zero," ASHRAE Journal, vol. 51, no. 9, pp. 18-25, 2009. Available: <https://www.ashrae.org>
- [3] International Energy Agency (IEA), "Net Zero by 2050 - A Roadmap for the Global Energy Sector," IEA Publications, 2021. Available: <https://www.iea.org/reports/net-zero-by-2050>
- [4] L. Bande et al., "Towards Sustainable Cities: A Review of Zero Energy Buildings Techniques and Global Activities in

Residential Buildings," *Energies*, vol. 16, no. 3, 2023. Available: <https://doi.org/10.3390/en16031383>

[5] S. Attia et al., "State of the Art of Architect Friendly Building Performance Simulation Tools," *Journal of Building Performance Simulation*, vol. 5, no. 2, 2012. Available: <https://doi.org/10.1080/19401493.2011.642038>

[6] Bureau of Energy Efficiency (BEE), "Eco Niwas Samhita (Energy Conservation Building Code for Residential Buildings)," Ministry of Power, Government of India, 2018. Available: <https://beeindia.gov.in/en/eco-niwas-samhita>

[7] Bureau of Indian Standards, "National Building Code of India(NBC)2016Volume2," BIS,2016.Available:<https://www.bis.gov.in/>

[8] GRIHA Council, "Green Rating for Integrated Habitat Assessment (SVAGRIHA) for Small Homes," The Energy and ResourcesInstitute(TERI),2019.Available:<https://www.griha.india.org/svagriha>

[9] Indian Green Building Council (IGBC), "IGBC Green Homes Rating System," Confederation of Indian Industry (CII), 2020. Available: <https://igbc.in/>

[10] M. Kaur and P. Singh, "Net Zero Energy Building Movement in India - An Overview," *Journal of Physics: ConferenceSeries*,2022.Available:<https://doi.org/10.1088/1742-6596/2273/1/012015>

[11] S. Raji, A. Tenpierik, and A. van den Dobbelen, "The impact of greening systems on building energy performance: A literature review," *Renewable and Sustainable Energy Reviews*,2015.Available:<https://doi.org/10.1016/j.rser.2015.01.054>

[12] A. Sharma et al., "Role of Passive Design and Alternative Energy in Building Energy Optimization," *International Journal of Scientific Research in Science, Engineering and Technology*,2020.Available:<https://doi.org/10.32628/IJSRST>

[13] S. Al-Saadi and A. Al-Jabri, "Passive Design for Residential Buildings in Arid and Semi-Arid Climates," *Building and Environment*, 2021. Available: <https://doi.org/10.1016/j.buildenv.2021.108152>

[14] M. B. C. et al., "Passive cooling techniques for buildings in hot and humid climates," *Renewable and Sustainable EnergyReviews*,2018.Available:<https://doi.org/10.1016/j.rser.2017.09.052>

[15] N. A. A. S. et al., "Optimization of window-to-wall ratio for high-performance buildings," *Energy and Buildings*, 2019.Available:<https://doi.org/10.1016/j.enbuild.2019.04.032>

- [16] B. Givoni, "Passive low energy cooling of buildings," Van Nostrand Reinhold, 1994. Available: <https://onlinelibrary.wiley.com/doi/book/10.1002/9780470172582>
- [17] A. R. K. et al., "Effectiveness of natural cross-ventilation in hot climates," *Journal of Wind Engineering and Industrial Aerodynamics*, 2017. Available: <https://doi.org/10.1016/j.jweia.2017.02.015>
- [18] S. M. et al., "Thermal mass and night ventilation utilized for building cooling," *Applied Energy*, 2016. Available: <https://doi.org/10.1016/j.apenergy.2015.12.016>
- [19] S. Manu, et al., "Field Studies of Thermal Comfort Across Multiple Climate Zones for the Subcontinent: India Model for Adaptive Comfort (IMAC)," *Building and Environment*, 2016. Available: <https://doi.org/10.1016/j.buildenv.2015.10.026>
- [20] ASHRAE, "Standard 55-2020: Thermal Environmental Conditions for Human Occupancy," American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2020. Available: <https://www.ashrae.org/>
- [21] R. de Dear and G. Brager, "Developing an adaptive model of thermal comfort and preference," *ASHRAE Transactions*, 1998. Available: <https://escholarship.org/uc/item/4qq2p9c6>
- [22] D. H. Li, et al., "A Study of Zero Energy Buildings and Sustainable Development Implications," *Energy and Buildings*, 2013. Available: <https://doi.org/10.1016/j.enbuild.2012.06.011>
- [23] T. V. Ramachandra et al., "Solar Energy Potential in Indian Regions," *Renewable and Sustainable Energy Reviews*, 2011. Available: <https://doi.org/10.1016/j.rser.2011.04.032>
- [24] I. B. et al., "Performance analysis of grid-connected rooftop solar PV systems in India," *Energy for Sustainable Development*, 2018. Available: <https://doi.org/10.1016/j.esd.2018.01.002>
- [25] Central Ground Water Board (CGWB), "Manual on Artificial Recharge of Ground Water," Ministry of Jal Shakti, Government of India, 2020. Available: <http://cgwb.gov.in/>
- [26] J. P. et al., "Rainwater harvesting in urban areas: technical and economic feasibility," *Water Science and Technology*, 2015. Available: <https://doi.org/10.2166/wst.2015.110>
- [27] M. E. et al., "Greywater reuse for sustainable residential water management," *Journal of Cleaner Production*, 2016. Available: <https://doi.org/10.1016/j.jclepro.2016.03.111>
- [28] Ministry of Housing and Urban Affairs (MoHUA), "Solid Waste Management Rules, 2016," Government of India, 2016. Available: <https://mohua.gov.in/>
- [29] A. K. et al., "Decentralized solid waste management in India: A systematic review," *Waste Management*, 2019. Available: <https://doi.org/10.1016/j.wasman.2019.03.056>
- [30] C. R. et al., "Circular economy in the built environment: A review," *Resources, Conservation and Recycling*, 2020. Available: <https://doi.org/10.1016/j.resconrec.2019.104443>