Developing a conceptual framework for Net-Zero Energy Building (NZEB) retrofitting of university buildings in tropical climates

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ABSTRACT

The global shift towards Net Zero Energy Buildings (NZEBs) has increased academic and policy interest in sustainably retrofitting existing buildings, especially in Higher Education Institutions (HEIs). University campuses or Higher Education Institutions constitute a substantial infrastructure network due to their extensive scale and varied construction typologies, with both direct and indirect environmental impacts. These campuses also serve as major energy consumers, living laboratories, and sustainability exemplars, offering a unique opportunity to advance NZEB transitions. Despite this increasing commitment, retrofitting existing university buildings, mainly in tropical climates, remains fragmented, technically skewed, and insufficiently theorised. Most retrofit initiatives and academic research still focus on technological solutions such as renewable integration and energy-efficient systems, while ignoring the crucial roles of occupant behaviour, economic realities, policy environments, and institutional structures. Many studies lack an integrated conceptual framework that systematically integrates technical retrofit solutions with institutional, behavioural, and policy dimensions, particularly in tropical climates and developing country contexts. Therefore, after an in-depth study of the conceptual, empirical, and theoretical literature, this study develops a conceptual framework to enable retrofitting existing university buildings to achieve NZEB performance in tropical regions. The study adopts Socio-Technical Systems Theory and Diffusion of Innovations Theory as additional lenses to better understand the dynamics of innovation adoption, implementation, and organisational behaviour in university environments. Addressing this gap is important to support integrated retrofit solutions, improve policy and administrative decision-making, and advance sustainable campus growth aligned with climate mitigation. The study concludes that achieving NZEB in tropical HEI's requires a holistic socio-technical approach that integrates technical solutions with behavioural, economic, institutional, policy and innovation-related factors. It recommends that university managers, policymakers, and built-environment professionals adopt integrated retrofit strategies supported by stakeholder engagement, institutional capacity, appropriate financing, and enabling policies and regulations. The proposed framework provides a basis for informed retrofit decision-making and future empirical validation in tropical HEIs.

Keywords: Conceptual Framework; Net Zero Energy Buildings; Sustainable Retrofitting; Socio-Technical Systems Theory; University Campuses

I. INTRODUCTION

Climate change is one of the most urgent global challenges of the 21st century, with the built environment accounting for approximately 36–40% of global energy consumption and associated carbon emissions (Ohene et al., 2022). Continued urbanisation, expanding building floor areas, and rising demand for mechanical cooling in tropical regions have further intensified building energy consumption, underscoring the urgent need for strategies to improve the energy performance of existing buildings (Jankovic et al., 2021; Razzaq et al., 2023). Net Zero Energy Buildings (NZEBs) are increasingly recognised as a key strategy for achieving low-carbon and climate-adaptive built environments. According to the Energy Performance of Buildings Directive [EPBD] of 2010, NZEBs are buildings with very high energy performance, where the resulting low energy demand is met through on-site or nearby renewable energy. Sustainable retrofitting has therefore gained increasing attention as an effective strategy for transforming existing buildings into energy-efficient, environmentally responsible assets while extending their operational lifespan (Ishak & Azizan, 2021). Within this broader transition, Higher Education Institutions (HEIs) occupy a unique position. These institutions serve as hubs for learning, innovation, and leadership in sustainability and are significant energy consumers due to their extensive infrastructure, high occupancy levels, and specialised facilities (Aleixo et al., 2018). However, many university buildings in the tropics were constructed before modern energy-

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efficiency standards and therefore have inefficient building envelopes, outdated cooling systems, and high operational energy demands. These characteristics present considerable challenges to achieving net-zero energy performance while simultaneously offering significant opportunities for sustainable retrofit interventions

Although research on Net Zero Energy Building (NZEB) retrofitting has expanded considerably over the past decade, much of the existing literature remains predominantly technology-oriented, focusing on energy-efficient systems, renewable energy integration, optimisation techniques, and simulation-based performance modelling. While these technological advancements are essential, they often overlook how occupant behaviour, institutional governance, economic constraints, stakeholder engagement, and policy environments shape retrofit implementation and long-term building performance. This narrow technological emphasis contributes to the well-documented building energy performance gap, whereby actual energy consumption frequently exceeds predicted performance because of operational practices, behavioural factors, and organisational shortcomings (Van de Putte et al., 2025). Chiesa et al. (2025) define the Energy performance gap as "*the difference between predicted and measured energy performance in buildings with mechanical systems for one or more energy services (space heating, cooling, ventilation, etc.)*". These challenges are particularly pronounced in tropical climates, where high temperatures, elevated humidity and substantial cooling loads demand climate-responsive retrofit strategies. Existing frameworks rarely capture interdependent socio-technical relationships, limiting their usefulness for guiding retrofit planning and implementation in Higher Education Institutions.

Addressing this gap requires a holistic conceptualisation of NZEB retrofitting that recognises universities as complex socio-technical systems in which technological innovation, organisational structures, stakeholder behaviour, governance mechanisms, and policy support interact to shape energy performance (Wang et al., 2026). Therefore, this study aims to develop an integrated conceptual framework for retrofitting existing university buildings towards NZEB performance in tropical regions. The framework integrates technical retrofit strategies with behavioural, institutional, economic, and policy dimensions that influence retrofit planning, implementation, and performance. Specifically, this study aims to identify and synthesise the key factors influencing NZEB retrofits in existing HEIs and establish their interrelationships within a coherent conceptual framework. The conceptual framework is intended to support university decision-makers, policymakers, and built-environment professionals in developing more holistic and context-specific retrofit strategies to advance NZEB transitions in tropical university settings.

1.1 Statement of the Problem

Retrofitting existing university buildings, particularly in tropical regions, remains largely focused on technical interventions such as energy-efficient systems, renewable energy integration, and building performance modelling, despite growing interest in NZEB transitions. This technology-focused approach inadequately accounts for occupant behaviour, institutional capabilities, economic constraints, governance, and policy factors that affect the adoption, implementation, and sustained effectiveness of retrofitting. The problem is further compounded in tropical university environments by high cooling demands, diverse building functions, and complex operational contexts, which can contribute to differences between predicted and actual energy performance (Van de Putte et al., 2025). Consequently, an integrated conceptual framework that systematically connects the technical, behavioural, institutional, economic, policy, and innovation-adoption dimensions of NZEB retrofitting is lacking, particularly within tropical and developing-country Higher Education Institutions. This gap limits holistic retrofit planning and informed decision-making and underscores the need for a context-responsive framework to guide the transition of existing university buildings towards NZEB performance (Wang et al., 2026). This study addresses this gap by proposing an integrated conceptual framework for NZEB retrofitting tailored to tropical university campuses.

1.2 Research Objectives

To address the existing gap, the study pursues the following objectives;

i. Examine the critical dimensions influencing NZEB retrofit outcomes in university buildings.
ii. Develop an integrated conceptual framework for NZEB retrofitting by synthesising the factors through Socio-Technical Systems Theory and Diffusion of Innovation Theory.
iii. Provide strategic insights for policymakers and university stakeholders to support effective retrofit implementation.

II. LITERATURE REVIEW

2.1 Theoretical Review

This study is theoretically anchored in the Socio-Technical Systems (STS) Theory and Diffusion of Innovations (DOI) Theory to explain the multidimensional nature of NZEB retrofitting in university environments.

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Together, the theories provide a basis for examining the technological, behavioural, organisational, and contextual factors that influence NZEB retrofit outcomes in university buildings.

2.1.1 Socio-Technical Systems Theory

Socio-Technical Systems (STS) Theory is an organisational perspective concerned with the relationships, interdependencies, and interactions between social and technical elements within a system. Kemp et al. (2024) describe STS as an approach that considers relationships between social elements, including people, structures, and culture, and technical components, including tasks, infrastructure, and technology. The theory suggests that one cannot fully understand the design and effectiveness of an organisational system by examining its technical components separately from the social system in which they operate. Rather, technical and social elements are interconnected and should be considered together to achieve effective system outcomes. STS theory is relevant to building retrofitting because retrofit interventions are not purely technical activities. Researchers have identified building retrofitting as a multifaceted socio-technical challenge that requires understanding of how physical arrangements facilitate sustainable practices, rather than viewing it merely as a technical problem to be resolved through technology installation and rational decision-making (Medrano-Gomez et al., 2025). Similarly, Falana et al. (2024) view ZEBs as a multifaceted socio-technical system that entails the development, diffusion, and application of technologies designed to achieve net-zero energy goals. Within university environments, NZEB retrofit outcomes depend on the interaction between technical interventions and social and institutional conditions. Factors such as occupant behaviour, stakeholder involvement, organisational practices, and management structures influence technology adoption, operation, and effectiveness. STS Theory therefore provides a useful lens for understanding these interdependencies and their influence on NZEB retrofit outcomes.

2.1.2 Diffusion of Innovations Theory

Diffusion of Innovations (DOI) Theory provides a complementary perspective by explaining how new ideas, technologies, and practices spread and become adopted within social systems. Rogers et al. (2014) describe diffusion as the process through which an innovation is communicated through particular channels over time among members of a social system. The theory is particularly relevant to NZEB retrofitting because retrofit measures involve introducing and adopting technologies and practices that may differ from existing building-management routines. NZEB retrofitting is a complex innovation process involving multiple stakeholders, including university administrators, facility managers, consultants, and building users. DOI theory describes the role of awareness, communication channels, institutional support, perceived benefits, and stakeholder networks in adopting and implementing retrofits. In developing country contexts, factors such as limited awareness, financial constraints, and weak institutional capacity continue to hinder the diffusion of sustainable retrofit innovations (Kalumba et al., 2025). Barriers such as limited awareness, weak policy support, financial constraints, and inadequate technical capacity also continue to impede the diffusion of NZEB practices (Kalumba et al., 2025).

Together, STS and DOI provide a comprehensive theoretical lens for understanding how technological systems, institutional structures, and behavioural processes shape NZEB retrofits in tropical university contexts. STS focuses on the interdependence between technical systems and the social and organisational environment, whereas DOI focuses on the adoption and diffusion of innovations within social systems.

2.2 Conceptual Review

2.2.1 Net Zero Energy Buildings

The building sector contributes significantly to global energy consumption and greenhouse gas emissions, underscoring the need for sustainable building solutions and low-carbon transitions (Ohene et al., 2024). In this context, Net Zero Energy Buildings (NZEBs) have emerged as an important strategy to improve building energy performance and reduce environmental impacts. According to the Energy Performance of Buildings Directive (EPBD), a nearly zero-energy building has very high energy performance, with its very low energy requirement covered to a significant extent by energy from renewable sources produced on-site or nearby. Different terminologies have been used across regions and regulatory frameworks, including Nearly Zero Energy Buildings (nZEBs), Zero Energy Buildings (ZEBs), and Net Zero Carbon Buildings (NZCBs). Although these concepts differ in their specific definitions and boundaries, they share the broader objective of reducing building energy demand and environmental impacts through energy efficiency and renewable energy integration (Hinge, 2018; Sartori et al., 2012). The NZEB concept, initially explored in the early 2000s, has gained increasing importance as governments and researchers seek to reduce greenhouse gas emissions from the building sector (Sabour et al., 2023). Lou and Hsieh (2024) note that the net-zero-energy building paradigm has become an important benchmark for future building development. NZEBs are particularly relevant to existing buildings because a substantial proportion of the global building stock was constructed

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before the introduction of modern energy-efficiency standards. Such buildings often exhibit poor thermal performance and high operational energy demand (Maduta et al., 2025). Retrofitting therefore offers an important pathway to improve the energy and environmental performance of existing buildings while extending their useful life (Jankovic et al., 2021; Pihelo et al., 2017).

2.2.2 Sustainable Retrofitting of Existing Buildings

Sustainable retrofitting refers broadly to interventions intended to improve the energy, environmental, and operational performance of existing buildings. Such interventions may involve modifications to the building envelope, mechanical and electrical systems, energy-management systems, and renewable energy infrastructure. Enow et al. (2025) describe sustainable retrofitting as involving interventions that improve energy efficiency, reduce greenhouse gas emissions, and enhance overall building performance through environmentally responsible technologies and materials. The literature generally identifies three broad categories of NZEB retrofit strategies: passive, active, and renewable energy measures (Qu et al., 2020). Passive measures aim to reduce building energy demand through interventions such as insulation, shading, glazing improvements, natural ventilation, daylight optimisation, and other building-envelope modifications (Friess & Rakhshan, 2017). Active measures involve improvements to mechanical and electrical systems, including HVAC, lighting, and water-heating systems. Renewable energy measures, including photovoltaic and solar thermal systems, can subsequently be introduced to offset the remaining energy demand. Albadry et al. (2017), for example, developed a process for achieving net-zero performance in existing buildings that begins with improvements to the building envelope, followed by reductions in energy consumption and the integration of renewable energy generation. Recent developments in smart technologies, building automation, energy-management systems, and real-time monitoring have further expanded the range of retrofit interventions available to improve building performance (Bassey et al., 2025). The effectiveness of retrofit interventions depends on how technologies interact with building occupants, operational practices, institutional arrangements, and management conditions.

2.2.3 University Buildings and NZEB Transitions in Tropical Climates

Higher Education Institutions (HEIs) are important stakeholders in sustainability through their teaching, research, campus operations, and community engagement (Aleixo et al., 2018). At the same time, these institutions are among the largest energy consumers because of their extensive infrastructure, high occupancy, diverse building functions, and intensive operational activities (Laporte & Casino, 2024). The expansion of university infrastructure and student enrolment in developing countries has further increased institutional energy demand. Also in tropical regions, high temperatures and humidity increase cooling requirements, while inadequate building envelopes, inefficient cooling systems, poor natural ventilation, and limited climate-responsive design can further increase energy demand (Bastida-Molina et al., 2023). Many university buildings were constructed before the adoption of contemporary sustainability and energy-efficiency standards and consequently exhibit characteristics that increase dependence on mechanical cooling (Awolesi, 2025). Evidence from Ghanaian universities demonstrates that these challenges are both technical and operational. HVAC systems represent a major share of university electricity consumption, with Tozar et al. (2023) estimating their contribution at approximately 55–65%, while ageing and inefficient air-conditioning systems further increase energy use, operational costs, and carbon emissions (Rauf et al., 2022; Nimoh et al., 2021). Building-related deficiencies, including poor orientation, thermal performance, and natural ventilation, also contribute to energy inefficiency (Amos-Abanyie et al., 2021). Beyond technical factors, inadequate maintenance, inefficient appliances and appliance use, rising energy costs, and poor energy management and occupant practices further increase consumption (Boafo et al., 2025; Amos-Abanyie et al., 2016). Although these findings are drawn from Ghana, they reflect challenges commonly reported across tropical Higher Education Institutions, where limited financial resources, ageing building stock, and increasing cooling demand constrain the implementation of sustainable retrofit programmes. These findings therefore demonstrate the importance of considering both technical and behavioural factors when examining NZEB retrofit outcomes. Existing evidence suggests that documented NZEB projects are concentrated largely in temperate developed countries, while implementation in tropical developing regions remains limited because of financial, institutional, and technological constraints (Chacón et al., 2022).

2.3 Empirical Review

The empirical review is organised around the study's objectives. It examines the critical dimensions influencing NZEB retrofit outcomes, evidence concerning adoption and implementation within HEIs, existing approaches for integrating these dimensions, and strategic implications for university stakeholders and policymakers.

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2.3.1 Critical factors influencing NZEB Retrofit

The literature identifies various interrelated factors that influence the successful implementation of NZEB retrofits in existing buildings. These factors are not only technological but also behavioural, institutional, financial and policy-related.

2.3.1.1 Technical Factors

Technical interventions underpin NZEB retrofit implementation. The literature identifies key strategies, including passive solar design, building envelope upgrades, energy-efficient HVAC systems, smart energy management systems, and the integration of renewable energy sources (Dabija, 2024; Wu & Skye, 2021). Passive design techniques such as shading, insulation, thermal optimisation, and natural ventilation are crucial for reducing cooling loads and operational energy consumption, especially in tropical regions. These techniques use natural environmental conditions to reduce dependence on mechanical systems by optimising building orientation, solar gain, and natural daylighting, and they can significantly reduce operational energy demand while improving occupant comfort (Dabija, 2024). After optimising passive measures, active measures, and on-site renewable energy systems can help achieve NZEB performance levels. Integrating intelligent building systems such as building automation, energy management, and real-time monitoring further improves energy optimisation (Kim & Lim, 2024). Despite these advances, technical challenges remain, especially during the design, retrofitting, and implementation phases, and discrepancies between predicted and actual building performance remain a major problem.

2.3.1.2 Behavioural and Stakeholder Factors

Occupant behaviours and stakeholder engagement also strongly influence the success of retrofit interventions. Research shows that energy-efficient technologies may not achieve expected savings if occupants operate buildings inefficiently or contrary to design assumptions (Zou et al., 2019). User practices regarding cooling systems, lighting, and equipment usage directly affect building energy consumption and contribute to the energy performance gap. Net-zero carbon buildings are socio-technical systems where the interplay between technological solutions and the organisational and social structures that support them is critical (Falana et al., 2026). Freeman and Phillips (2002) define stakeholders as individuals or organisations involved in or affected by a project. Falana et al. (2026) also argue that identifying and classifying stakeholders, following stakeholder partnership management principles, is paramount to successfully implementing net zero carbon buildings. As Molwus et al. (2017) point out, overlooking a key stakeholder or misinterpreting their role can seriously hinder project progress. A case study illustrating successful stakeholder engagement is the Richardsville Elementary School project in Kentucky, USA, which became the first NZEB-certified school in the United States upon completion in 2010. The project's success was attributed not only to its energy-efficient design and on-site renewable generation but also to the extensive engagement with students, teachers and the wider community (Iyiegbuniwe, 2014). Integrating educational components within the project raised awareness of sustainable practices and supported the long-term cultural adoption of sustainability principles. This example highlights the importance of including facility managers, building occupants and external partners in design and operational decision-making. Successful retrofits require collaboration among university administrators, facilities managers, consultants, policymakers, and building occupants (Vakeva-Baird et al., 2025). Early stakeholder engagement facilitates knowledge sharing, improves project acceptance, and supports long-term operational success (Olander & Landin, 2005). Educational programmes, behavioural interventions, and awareness campaigns have also been shown to improve energy-conscious behaviour within university environments.

2.3.1.3 Economic and Financial Factors

Economic feasibility is one of the most important determinants for NZEB retrofits, especially in developing countries with limited financial resources. The high upfront costs of retrofitting technologies, renewable energy systems, and building upgrades often deter implementation, despite potential long-term savings (Trivedi et al., 2023). The literature review shows that high initial investment costs are a major barrier to NZEB implementation. These costs are usually offset by long-term economic benefits such as lower or no utility bills, increased asset value, and better resilience to fluctuating energy prices. However, Jareemit et al. (2022) note that uncertainty about future energy prices and technology costs increases financial risk, especially for retrofitting projects. Tozer et al. (2023) also note that the payback period strongly influences investors' decisions on retrofitting and decarbonisation projects. They suggest that NZEB and ZCB projects often require a longer-term commitment, and the payback period is an important factor for investors and building owners to consider. Akomea-Frimpong et al. (2025) expand on this by emphasising that the financial feasibility of ZCB projects depends on access to long-term capital and stable investment conditions. The literature further highlights the importance of financial incentives, grants, green financing mechanisms, and lifecycle cost analysis in improving retrofit feasibility (Jareemit et al., 2022). While NZEB retrofits often entail higher initial costs than conventional building upgrades, studies indicate that operational energy savings, reduced utility

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expenses, and improved asset performance can offset these investments over time (Tozer et al., 2023). However, uncertainties surrounding payback periods and access to financing continue to limit widespread adoption.

2.3.1.4 Policy and Institutional Factors

Policy and institutional factors are critical to shaping NZEB transitions. Governments and regulatory bodies are increasingly pushing energy-efficient buildings through building codes, energy performance standards, renewable energy policies, and sustainability targets (Hinge, 2018). The European Union's Energy Performance of Buildings Directive (EPBD) is one of the most influential policy frameworks driving NZEB adoption globally. For example, the EPBD required all new public buildings to meet nearly zero-energy standards by December 2018 and expanded this requirement to all new buildings across the EU by December 2020. Since the EPBD, a proliferation of ZEB-related policies and initiatives has emerged across IPEEC member states and other national and sub-national governments. However, in developing nations, weak enforcement mechanisms, limited institutional capacity, and insufficient regulatory incentives often hamper retrofit implementation. Research indicates that supportive government policies, tax incentives, net metering systems and sustainability regulations are essential to accelerate the adoption of NZEBs (Trivedi et al., 2023). Institutional leadership in universities is also critical, as organisational commitment, governance structures and sustainability planning significantly influence retrofit implementation and operational performance. In addition to government leadership, non-governmental organisations and industry associations have made significant contributions to advancing the NZEB agenda. The World Green Building Council's global commitment to achieving 100% Net Zero Carbon Buildings by 2050 demonstrates how industry-led initiatives complement regulatory frameworks. Green Building Councils across different regions work with government agencies to establish voluntary certification schemes and foster market transformation towards zero-energy or zero-emission buildings.

2.3.1.5 Tropical Climate and Contextual Dimension

The tropical climate represents an important contextual dimension influencing NZEB retrofit outcomes. High temperatures and humidity can generate significant cooling demand, while poor building orientation, inadequate shading, inefficient envelopes, and limited natural ventilation can increase dependence on mechanical cooling (Tackaberry et al., 1997; Amos-Abanyie et al., 2021). These conditions make passive cooling, shading, natural ventilation, and efficient building envelopes particularly important in tropical retrofit strategies (Mengaw et al., 2024). At the same time, tropical regions offer opportunities for solar energy generation and passive environmental control. However, financial, technological, and institutional challenges constrain NZEB retrofit implementation in tropical developing countries (Chacón et al., 2022). The tropical context therefore influences not only the selection of appropriate technical interventions but also the economic, institutional, and operational feasibility of retrofit strategies.

2.3.2 NZEB Retrofit Adoption and Implementation in HEIs

The reviewed literature indicates that NZEB retrofit implementation involves processes of technological adoption, stakeholder acceptance, organisational adjustment, and operational change. This aligns with DOI Theory, which emphasises communication, perceived benefits, social systems, and adoption processes, and with STS Theory, which highlights interactions between technical systems and social and organisational structures. In university environments, retrofit innovations are introduced into established organisational and operational systems involving administrators, facility managers, staff, students, consultants, and policymakers. Their adoption may therefore depend on awareness, communication, perceived benefits, financial feasibility, technical capacity, institutional support, and stakeholder participation (Kalumba et al., 2025). The empirical evidence on occupant behaviour and stakeholder engagement further indicates that successful implementation requires users and institutional actors to understand, accept, and support changes in technologies and operational practices. The literature therefore suggests that retrofit implementation should not be viewed as a linear process in which technologies are simply selected and installed. Instead, implementation involves interaction between technological interventions, organisational structures, stakeholder behaviour, financial resources, and policy conditions. This provides empirical support for using STS and DOI as complementary theoretical lenses to examine NZEB retrofit adoption and implementation in HEIs.

2.3.3 Integration of Critical Dimensions in NZEB retrofit Frameworks

The reviewed studies demonstrate that technical, behavioural, economic, institutional, and policy factors each influence building energy performance and retrofit implementation. However, researchers often examine these dimensions independently. Technical studies tend to focus on energy-efficiency measures, renewable energy technologies, and building performance, while behavioural studies focus on occupants and energy-use practices. Similarly, economic studies emphasise investment costs and payback, whereas policy and institutional studies focus on regulation, governance, and organisational capacity. Separating these dimensions creates a limitation because one dimension's effectiveness can depend on conditions in another. For example, the technical feasibility of a retrofit may

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not translate into implementation if financing is unavailable, institutional support is weak, or occupants do not adopt appropriate operational practices. Likewise, supportive policies may have limited impact if universities lack the technical and financial capacity to implement the required measures. The literature therefore indicates a need for an integrated approach that captures the interrelationships among these dimensions. In this study, the identified constructs are brought together using STS and DOI as the theoretical lenses. This integration provides the basis for developing a conceptual framework that reflects the technical, social, organisational, economic, policy, and contextual conditions influencing NZEB retrofit implementation in HEIs.

III. METHODOLOGY

3.1 Research Design

This study adopted a qualitative exploratory research design to develop an integrated conceptual framework for retrofitting university buildings toward Net Zero Energy Building (NZEB) performance in tropical climates. A qualitative approach was appropriate because the study explores complex socio-technical interactions and synthesises diverse perspectives on retrofit implementation, institutional practices, occupant behaviour, and policy environments. The study employed two primary methods: a structured literature review and semi-structured expert interviews. The literature review identified and synthesised existing theoretical, conceptual, and empirical knowledge on NZEB retrofitting, while the expert interviews provided contextual insights into implementation challenges and critical success factors within university environments. The study is grounded in Socio-Technical Systems Theory and Diffusion of Innovations Theory, which informed both data interpretation and the development of the conceptual framework.

3.2 Literature Search Strategy

This study's literature review was a structured, comprehensive analysis of scholarly articles, reviews, and other relevant publications on NZEB retrofitting, sustainable campus development, occupant behaviour, and tropical climate challenges. The objective was to capture the breadth of relevant concepts and current knowledge on Zero Energy buildings in Higher Education Institutions. This method facilitates identifying critical themes, trends, and knowledge gaps across numerous subtopics, establishing a foundational understanding of recent developments and obstacles in the field. The review contributes to a conceptual framework that informs subsequent case study analyses and directs the research toward practical and emerging issues in sustainable buildings by synthesising findings from diverse sources.

3.3 Expert Interviews and Sampling

Semi-structured expert interviews were conducted to obtain contextual and professional insights into the factors influencing NZEB retrofit implementation in university buildings in tropical climates. The interviews complemented the literature review by exploring practical experiences and challenges relating to sustainable building retrofits in higher education institutions (HEIs). Purposive sampling identified participants with relevant expertise in sustainable buildings, energy systems, university infrastructure and facilities management, architecture, environmental sustainability, and energy policy. Participants were selected based on their professional experience and familiarity with building retrofit and energy-performance challenges in tropical contexts.

Five experts from diverse built-environment disciplines participated in the study. Although the sample was small, it was appropriate for the exploratory qualitative design, which sought depth of professional insight rather than statistical generalisation. The sample's interdisciplinary composition provided perspectives on the technical, environmental, behavioural, institutional, economic, and policy dimensions relevant to NZEB retrofits. The semi-structured interview guide was developed from the literature review and informed by the study's theoretical perspectives, Socio-Technical Systems (STS) Theory and Diffusion of Innovations (DOI) Theory. Questions addressed energy-performance challenges, retrofit barriers, institutional and financial constraints, policy and governance, technical strategies for achieving NZEB performance, and occupant behaviour and operational practices. Interviews lasted approximately 30–45 minutes and were conducted in person or virtually; with participants' consent, they were audio-recorded before transcription and thematic analysis. Participants are identified throughout the findings using anonymised codes **P1–P5** to protect confidentiality. These codes are used consistently to attribute interview quotations and participant perspectives. The interview findings were then compared with the literature to identify and refine the themes informing the integrated conceptual framework.

3.4 Data Analysis and Thematic Development

The data obtained from the structured literature review and semi-structured expert interviews were analysed using thematic analysis following Braun and Clarke’s (2006) six-step analytical framework. Thematic analysis was

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considered appropriate for the study's objective of identifying recurring patterns, meanings, and relationships across a range of socio-technical dimensions influencing the retrofitting of NZEBs in university buildings in tropical climates. The approach also facilitated the incorporation of theoretical insights from Diffusion of Innovations (DOI) Theory and Socio-Technical Systems Theory (STS) into the interpretation of the findings. The initial phase of the analysis involved data familiarisation, which included repeated review of interview transcripts and literature findings to develop a comprehensive understanding of emerging issues related to retrofit implementation, energy performance, stakeholder behaviour, institutional governance, and policy support mechanisms. During this phase, reflective memoranda and observational notes were created to document recurring concepts and preliminary interpretations. Next, initial codes were generated from empirical and theoretical sources using inductive and deductive approaches. Inductive coding allowed themes to emerge directly from the interview data, whereas deductive coding was guided by relevant literature on NZEB retrofitting and the study's theoretical underpinnings. Codes such as "occupant energy behaviour," "institutional leadership," "cooling demand," "financial barriers," "passive retrofit," "stakeholder engagement," and "smart monitoring systems" were consistently recognised throughout the dataset. The coded data were subsequently organised into wider thematic categories through an iterative comparison process. Codes with shared similarities and connections were organised into broader themes that illustrate the essential aspects influencing NZEB retrofit implementation. The analysis identified five key themes: technical and environmental factors; occupant behaviour and operational practices; institutional and governance structures; economic and financial considerations; and Policy and regulatory support mechanisms.

These themes were then reviewed and refined for coherence and conceptual consistency. The refinement process involved a detailed comparison of the interview findings with insights from the existing literature to establish convergence and thematic consistency. The literature strongly supported the interview findings, indicating that NZEB retrofitting is not only a technological process but a complex socio-technical transition that requires interaction between technical, institutional, behavioural, governance and policy mechanisms. Similarly, the analysis revealed a strong alignment with socio-technical systems theory and diffusion of innovation theory, highlighting the interdependence between human behaviour and technological systems and how retrofit innovations are communicated, accepted, and institutionalised within university environments. The stage involved synthesising the themes into an integrated conceptual framework that explains NZEB retrofitting as a dynamic socio-technical transition process within tropical university buildings.

To strengthen the rigour and trustworthiness of the thematic analysis, the study drew on the criteria proposed by Lincoln and Guba (1985): credibility, transferability, dependability, and confirmability, as operationalised for thematic analysis by Nowell et al. (2017). Credibility was supported through familiarisation with the full dataset prior to coding and through constant comparison between emerging codes and the literature-derived theoretical categories (STS and DOI theory) during the refinement stage. Dependability and confirmability were supported by maintaining a decision trail that documented how initial codes were grouped into the five broader themes, allowing the analytical process to be traced from the raw transcript to the final themes. Given the interdisciplinary composition of the five-expert sample (spanning architecture, sustainability, facilities management, energy systems, and environmental policy), transferability is interpreted cautiously: the themes are likely to resonate with other tropical HEI contexts sharing similar climatic and institutional conditions, but the small, purposive sample means the findings should be read as analytically rather than statistically generalisable. Given the modest sample size, coding was conducted manually through iterative matrix comparison of transcripts and literature themes rather than qualitative analysis software.

IV. FINDINGS & DISCUSSION

4.1 Findings

4.1.1 Integrated Nature of NZEB Retrofitting

The findings indicate that achieving NZEB performance in tropical university buildings requires comprehensive socio-technical coordination across technical systems, occupant practices, institutional governance, financial mechanisms, policy support structures, and technological upgrades. While previous studies have largely emphasised energy-efficient technologies and renewable energy integration, this study shows that retrofit success depends on aligning technical and social systems within Higher Education Institutions (HEIs). This finding reinforces the central proposition of Socio-Technical Systems (STS) Theory, which argues that organisational performance emerges from the interaction between technological infrastructure and social structures. The thematic analysis identified five interrelated dimensions influencing NZEB retrofitting: ***technical and environmental factors; occupant behaviour and operational practices; institutional and governance structures; economic and financial considerations; and policy and regulatory support.*** Rather than functioning independently, these dimensions collectively shape retrofit planning, implementation, and long-term operational performance. This supports previous

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studies by Falana et al. (2024), Tweed (2013), Vakeva-Baird et al. (2025) and Asante et al. (2026), which recognise that building energy performance is influenced not only by technological measures but also by organisational practices, stakeholder engagement, and occupant behaviour. The findings also extend the application of Diffusion of Innovations (DOI) Theory by demonstrating that successful retrofit implementation depends on institutional leadership, stakeholder communication, and organisational commitment to sustainability. From this perspective, NZEB retrofitting represents both a socio-technical transition and an organisational innovation process, requiring technological improvements to be accompanied by effective governance, behavioural change, and supportive policy environments. Collectively, these findings provide the conceptual basis for the integrated framework proposed in this study by showing that NZEB retrofitting in tropical university buildings is a dynamic socio-technical process in which technical, behavioural, institutional, financial, and policy dimensions operate as interconnected rather than independent components.

4.1.2 Technical and Environmental Dimensions of Retrofit Performance

Findings indicate that technical and environmental conditions are important considerations in reducing operational energy demand in university buildings. Participants particularly emphasised the influence of the tropical climate, where high cooling demand, substantial solar exposure, and elevated humidity create specific challenges for building energy performance. These conditions were considered to require climate-responsive retrofit approaches rather than directly applying strategies developed for temperate environments. Passive retrofit measures, including shading systems, roof insulation, natural ventilation, daylight optimisation, and thermal envelope improvements, were identified as important approaches to reduce cooling loads and improve building performance. Participants P1 and P3 particularly emphasised addressing energy demand through passive measures before introducing renewable-energy systems. As one participant stated: *"Passive design strategies should be prioritised before renewable systems are introduced."* (P1, 4th March, 2026).

This finding is consistent with Friess and Rakhshan (2017) and Geels (2002), who highlight the contribution of climate-responsive passive strategies to reducing cooling demand and improving building performance in tropical environments. The findings further suggest that retrofit strategies for university buildings in tropical climates should adapt to local climatic conditions, with an emphasis on reducing energy demand and improving efficiency before introducing renewable-energy generation. The interviews also highlighted the importance of technologies that enable building energy performance to be observed and managed after retrofit implementation. Participants identified real-time energy analytics and smart monitoring systems as useful for identifying operational inefficiencies and supporting improvements in building performance. These findings are considered further alongside other interview evidence during the development of the integrated conceptual framework.

4.1.3 Occupant Behaviour and Socio-Technical Energy Gap

Occupant behaviour emerged as a critical determinant of building energy performance. Participants consistently reported that inefficient operational practices and limited energy awareness often reduce the effectiveness of technical retrofit measures. As P2 noted, *"Even when efficient systems are installed, energy wastage continues if users are not conscious of how they operate the building."* (P2 4th March, 2026). This finding supports previous research demonstrating that behavioural factors contribute significantly to the energy performance gap observed in buildings. The results suggest that awareness programmes, stakeholder engagement, and energy feedback systems are essential for encouraging energy-conscious behaviour across university campuses. Within the STS framework, building performance depends on interactions between technological systems and human practices, with occupant decisions about cooling, lighting, and equipment operation directly influencing operational energy consumption. Consequently, behavioural interventions should complement technical upgrades rather than stand alone. These findings informed the conceptual framework by identifying occupant behaviour as a cross-cutting socio-technical factor that supports the long-term effectiveness of NZEB retrofit strategies.

4.1.4 Institutional Governance and Innovation Adoption

Institutional commitment and governance structures emerged as important factors influencing the implementation of NZEB retrofits in university buildings. Participants identified fragmented organisational arrangements, limited coordination of sustainability activities, and inadequate institutional commitment as barriers to effective retrofit implementation. In particular, participants P3 and P4 emphasised the importance of leadership in translating sustainability objectives into practical action: *"Retrofit implementation requires strong leadership commitment; otherwise, sustainability policies remain theoretical."* (P3, 5th March, 2026).

The findings suggest that leadership commitment is important for aligning sustainability objectives with institutional priorities, resource allocation, and operational practices. Participants also highlighted the need for coordination among relevant stakeholders to facilitate decision-making and implementation across different university

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units. This indicates that retrofit implementation goes beyond adopting technical measures and requires institutional structures that support coordination, communication, and sustained organisational commitment. The findings also align with the Diffusion of Innovations perspective, particularly the role of communication, institutional support, stakeholder networks, and perceived benefits in facilitating innovation adoption. Within university settings, these conditions can influence how retrofit practices are understood, accepted, and incorporated into existing organisational practices. Effective governance and institutional coordination are therefore important for translating sustainability policies into implementable actions and supporting the longer-term integration of retrofit initiatives into university planning and operations.

4.1.5 Financial Constraints and Retrofit Feasibility

Financial constraints emerged as a significant barrier to implementing NZEB retrofits in tropical developing contexts. Participants identified high upfront investment costs, limited access to financing, and uncertainty regarding long-term payback periods as key challenges affecting retrofit adoption. As one participant explained:

"The biggest challenge is the initial investment cost, especially for renewable energy systems and integrated retrofit measures." (P5, 5th March, 2026).

These findings align with Trivedi et al. (2023), Tozer et al. (2023), and Akomea-Frimpong et al. (2025), who identify economic feasibility and financing constraints as key considerations in building retrofit adoption. Despite the initial financial barriers, participants also recognised the longer-term economic benefits associated with NZEB retrofits, particularly reduced energy expenditure, energy savings, and improved building performance. The findings therefore suggest that the financial feasibility of retrofit projects should be considered beyond initial capital costs, with attention to long-term operational savings and investment returns. Participants further highlighted the importance of accessible financing mechanisms, appropriate incentives, and public–private partnerships in reducing financial barriers and improving the feasibility of NZEB retrofit implementation in higher education institutions.

4.1.6 Policy and Regulatory Factors

The findings indicate that policy frameworks and institutional regulations influence the implementation of NZEB retrofit initiatives. Participants identified weak enforcement of energy-efficiency standards, limited institutional sustainability policies, and inadequate regulatory incentives as barriers to retrofit investment. Participants P2 and P3 emphasised the importance of policy and financial support: *"Without institutional policies and government incentives, universities struggle to prioritise retrofit investments."* (P2, 6th March, 2026). Participants further highlighted the need for stronger national energy policies, comprehensive university sustainability guidelines, and regulatory incentives to encourage investment in retrofit projects. These findings align with previous research showing that supportive policy and regulatory environments can reduce uncertainty and create conditions conducive to building energy-efficiency investments.

The findings also align with the Diffusion of Innovations (DOI) perspective, particularly the role of institutional support in facilitating innovation adoption. Supportive policies and regulations can enhance the legitimacy of retrofit innovations, reduce uncertainty about their adoption, and provide an enabling environment for integrating them into organisational practices. From this perspective, the adoption of retrofit technologies is also influenced by their perceived relative advantage, compatibility with existing institutional practices, technical complexity, and acceptance among relevant stakeholders. The findings therefore suggest that effective policy enforcement, institutional sustainability policies, and appropriate regulatory incentives are important for creating an enabling environment for the sustained adoption of NZEB retrofit practices in university buildings.

4.2 Framework Development

4.2.1 Development of the Integrated Conceptual Framework

The conceptual framework was developed through an iterative synthesis of evidence from the structured literature review and the thematic analysis of expert interviews. The development process was guided by the need to address a limitation identified in the literature: existing approaches to NZEB retrofitting tend to emphasise technical interventions, while giving comparatively less attention to the behavioural, institutional, financial, and policy conditions that influence retrofit implementation and sustained performance, particularly in university buildings within tropical climates. The framework therefore sought to integrate technical measures with the wider conditions required for their adoption, implementation, operation, and long-term effectiveness.

The first stage of framework development involved identifying the principal factors emerging from the literature and then examining them against evidence from the expert interviews. The thematic analysis produced five interconnected themes: *technical and environmental factors; occupant behaviour and operational practices; institutional and governance structures; economic and financial considerations; and policy and regulatory support*. These themes provided the empirical basis for identifying the conditions and processes that influence NZEB retrofit

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implementation. Rather than reproducing the themes as separate components of the framework, the study synthesised them by their role in the retrofit process. The second stage involved grouping the identified factors into broader dimensions that describe how NZEB retrofit implementation occurs. This process resulted *in* ***five interconnected dimensions: (1) Input Factors (Critical Success Factors), (2) Support Mechanisms (Enablers), (3) Retrofit Strategies (Key Technical Measures), (4) Monitoring and Operation (Performance Management), and (5) Outcomes (Towards NZEB)***. The empirical themes differ from the framework dimensions. The themes describe what the empirical investigation identified as important, whereas the dimensions explain how these factors are organised and operate within the retrofit process.

The first dimension, Input Factors (*Critical Success Factors*), represents the technical, environmental, behavioural, institutional, economic, and policy conditions that shape retrofit decision-making and implementation readiness. The tropical climate context is particularly relevant within this dimension because high cooling demand, solar exposure, humidity, and operational energy intensity influence the technical requirements and priorities of university building retrofits. Other factors identified through the interviews, including occupant behaviour, institutional capacity, financial resources, stakeholder considerations, and policy conditions, similarly influence the feasibility and direction of retrofit decisions. The second dimension, Support Mechanisms (*Enablers*), captures how the identified conditions translate into coordinated implementation. These include leadership commitment, stakeholder engagement, institutional coordination, funding mechanisms, policy support, awareness creation, and technical expertise. Including this dimension reflects the finding that favourable conditions alone do not necessarily lead to retrofit implementation. Organisational leadership, governance, coordination, resources, and institutional support are required to mobilise those conditions and facilitate the adoption of retrofit interventions. The third dimension, Retrofit Strategies (*Key Technical Measures*), represents the interventions that improve building energy performance. The strategies identified from the literature and supported by the expert findings include passive and demand-reduction measures, building envelope improvements, energy-efficient building systems, renewable-energy integration, and smart energy technologies. The framework reflects the principle that energy demand reduction and efficiency should be prioritised before introducing renewable-energy generation, while recognising that the appropriate combination of measures must respond to the building's climatic and operational characteristics. The fourth dimension, Monitoring and Operation (*Performance Management*), reflects the processes needed to maintain and improve building performance after retrofit interventions are implemented. These include energy audits, smart metering, real-time monitoring and analytics, maintenance, operational optimisation, and behavioural feedback. Including this dimension recognises that technology alone cannot assure retrofit performance. Continuous monitoring and effective operation provide the information required to identify performance gaps, optimise building systems, support adaptive learning, and inform subsequent improvements. The fifth dimension, Outcomes (Towards NZEB), represents the intended results of the interaction among the preceding dimensions. These outcomes include reduced energy consumption, improved energy efficiency, increased utilisation of renewable energy, reduced operational costs and emissions, improved thermal comfort, and enhanced overall building performance, ultimately contributing towards NZEB performance. Outcomes therefore result from the interaction between the conditions supporting retrofit implementation, the mechanisms that enable implementation, the technical interventions adopted, and their subsequent operation and management.

To organise these relationships within a broader socio-technical context, this study used the Multi-Level Perspective (MLP) developed by Geels (2002) as an organising framework. MLP distinguishes between landscape, regime, and niche levels, providing a useful structure for positioning the broader contextual environment, established university systems, and emerging retrofit innovations in relation to one another. In this study, MLP does not constitute an additional framework dimension or theoretical foundation; rather, it provides the organisational structure through which the relationships among the five dimensions can be viewed within the wider socio-technical transition towards NZEB performance. The broader environmental, policy, and societal conditions are therefore positioned as contextual influences, while the university's established organisational and operational conditions and the introduction of retrofit innovations provide the setting within which the five dimensions interact. The landscape level captures the broader contextual and enabling environment, including climate conditions, national agendas, policy, and governance, which create pressures and opportunities for NZEB transitions. The regime level encompasses the established university socio-technical system, represented by the Input Factors and Support Mechanisms that shape retrofit decision-making and implementation capacity. The niche level represents emerging innovations and practices, captured by Retrofit Strategies and Monitoring and Operation, through which retrofit interventions are implemented, evaluated, and refined. NZEB Outcomes represent the intended results of interactions across these levels, while continuous monitoring, learning, and improvement provide feedback for subsequent decision-making. Thus, MLP provides the organisational lens through which the five core dimensions: *Input Factors, Support Mechanisms, Retrofit Strategies, Monitoring and Operation, and NZEB Outcomes* are positioned within the broader socio-technical transition towards NZEB performance.

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The resulting framework therefore conceptualises NZEB retrofit implementation as an integrated socio-technical process in which technical interventions are supported by behavioural, organisational, financial, and policy conditions and are subject to continuous performance management. The framework is grounded theoretically in Socio-Technical Systems (STS) Theory and Diffusion of Innovations (DOI) Theory. STS theory informed the integration of technical and social dimensions by recognising the interdependence of building technologies, occupant behaviour, organisational structures, and operational practices. DOI theory informed the consideration of how retrofit innovations are communicated, adopted, and embedded within university settings, particularly through leadership, stakeholder engagement, communication, institutional support, and perceived benefits. MLP complements these theoretical foundations by providing the organisational lens through which the broader contextual environment, university socio-technical system, and retrofit innovations can be situated. The resulting framework (Figure 1) consequently provides an integrated basis for examining how existing university buildings in tropical climates can transition towards improved energy performance and NZEB outcomes.

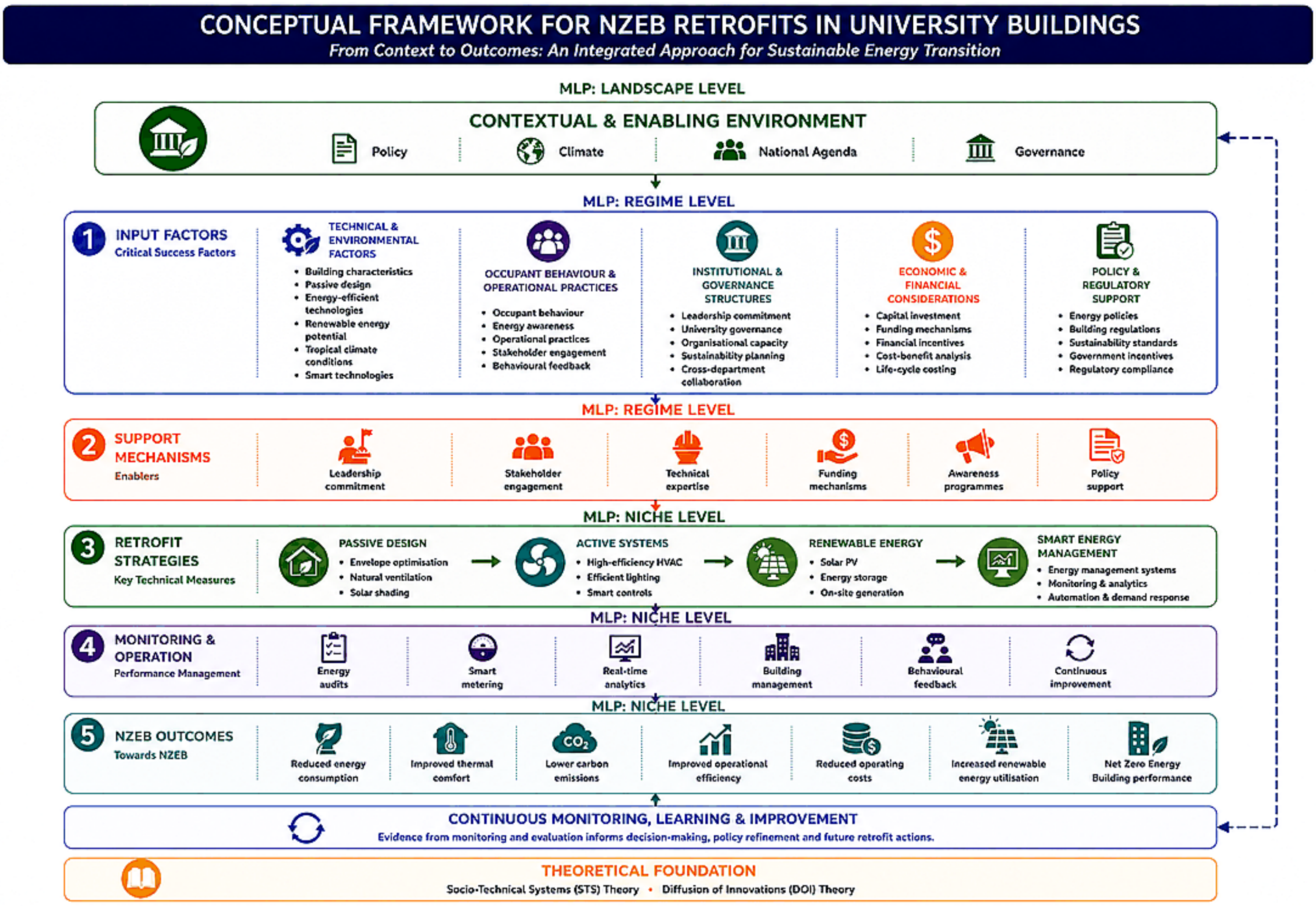

Figure 1
An Integrated Socio-Technical Innovation Framework for NZEB Retrofitting in Tropical University Buildings

V. CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

The study demonstrates that achieving Net Zero Energy Building (NZEB) performance in tropical university buildings requires a shift from isolated technological interventions towards an integrated socio-technical approach. Although passive design, energy-efficient technologies, and renewable energy systems are important for reducing operational energy demand, the findings show that successful retrofit implementation is also influenced by occupant behaviour, institutional commitment and governance, financial capacity, stakeholder engagement, and policy and regulatory support. The study therefore contributes an integrated socio-technical conceptual framework that brings these interrelated factors together within the specific climatic and institutional context of tropical Higher Education Institutions (HEIs). Grounded in Socio-Technical Systems Theory and Diffusion of Innovations Theory and organised around the Multi-Level Perspective (MLP) on socio-technical transitions, the integrated framework provides a basis

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for understanding and coordinating the technical, behavioural, institutional, financial, and policy conditions required to support NZEB retrofit implementation and sustained performance.

Based on these findings, universities should adopt integrated retrofit planning approaches that prioritise energy-demand reduction and efficiency before renewable-energy integration, while ensuring that retrofit decisions are informed by tropical climatic conditions and building-specific performance requirements. University leadership should strengthen institutional governance, stakeholder coordination, technical capacity, and long-term sustainability planning to support retrofit implementation. Policymakers should strengthen energy-efficiency regulations, institutional sustainability requirements, financial incentives, and accessible financing mechanisms to reduce barriers to retrofit investment. Facilities managers and built-environment professionals should incorporate continuous energy monitoring, performance evaluation, maintenance, and operational optimisation into retrofit programmes to sustain performance improvements.

5.2 Recommendations

The study recommends that universities adopt integrated retrofit planning that combines technical, behavioural, institutional, financial and policy considerations. They should also prioritise energy-demand reduction and efficiency before renewable-energy integration, while strengthening institutional leadership, stakeholder coordination, technical capacity, and long-term sustainability planning. Policymakers should support retrofit adoption through effective energy-efficiency regulations, incentives, and accessible financing, while facilities managers should institutionalise monitoring and performance management by embedding continuous energy monitoring, maintenance, and operational optimisation into retrofit programmes. The proposed framework remains an exploratory conceptual contribution and requires empirical validation. Future research should test and refine it using operational performance data and longitudinal case studies across diverse tropical university contexts, including comparative and quantitative approaches to assess its applicability and the relationships among its dimensions.

Declaration of Interest

The authors declare that they do not have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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