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Green Building Development in Sarawak, Malaysia: A Comprehensive Approach to a Sustainable Future and Net-Zero Buildings by 2050

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ABSTRACT: The overall global consumption of energy and carbon emissions from the building sector is significant, and therefore building construction is a key area for achieving net zero emissions by the year 2050. This article uses PRISMA-lite structured narrative review methodology and thematic synthesis to provide an overview of green building development and net zero pathways in Sarawak, Malaysia. This review is based on publications from 2010 to 2025 published on Scopus, Web of Science, ScienceDirect, and Google Scholar. The review uses a qualitative thematic synthesis method with descriptive quantitative analysis to include 4 distinct dimensions: policy frameworks, technological innovations, financing mechanisms, and stakeholder dynamics. Overall, the study indicates that the two most studied strategies are energy efficiency and renewable energy integration (72% and 65%, respectively). Additionally, Policy and Governance (60%) and Lifecycle Carbon Assessment (55%) represent two additional major research clusters. While there are many types of technological solutions available, including passive design systems, smart technologies, and materials that have low carbon footprints, their use is limited by insufficient policy enforcement and financial constraints, as well as the lack of coordination among stakeholders. Additionally, there is a consistent gap between designers' predicted performance versus the performance of buildings during operation; this is especially so in the context of developing countries with tropical climates. The goal of this study was to create a comprehensive policy-technology-finance-stakeholder framework to portray green building transitions as a combination of both socio and technical systems instead of identifying them as only technical problems. The study concluded that achieving net-zero buildings in Sarawak by 2050 is technically possible but will require more efficient institutional coordination, financial innovations, and capacity development.

1. INTRODUCTION

1.1 Green Buildings and Sustainable Development

The built environment is the main source of global environmental degradation and climate change, which makes it the main sector in sustainability transitions. According to reports from the International Energy Agency [1, 2], buildings use approximately 30% of the world's final energy supply as well as 26% of the total CO_2 emissions caused from using energy worldwide. In terms of the total carbon emissions from the built environment, about 33%, once you include emissions created by the building materials during construction.

Recent global assessments indicate that building-related operational emissions reached approximately 9.8 giga tones of CO_2 in 2023, with additional embodied emissions from materials such as cement, steel, and aluminum contributing significantly to lifecycle impacts[3]. This indicates that decarbonization must go further than just the energy used in operation; it must also include material production as well as construction processes[4].

Approximately 14 to 15 percent of all energy consumed in Malaysia comes from the building sector; most of that demand is generated by both combined residential and commercial buildings [5]. Therefore, this represents a significant sector of the economy in terms of energy security and decarbonizing Malaysia.

Green buildings are defined as those that positively impact the environment by minimizing their ecological footprint while maximizing resource use efficiency and maximising the health of their occupants throughout the building's life cycle[6, 7]. Unlike other types of buildings, green buildings incorporate energy efficiency, water conservation, use of sustainable materials, indoor environmental quality, and solid waste minimization into a holistic design and operations approach[8]. From a sustainability governance standpoint, green buildings support the implementation of global frameworks such as the UN Sustainable Development Goals (SDGs) related to affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), and climate action (SDG 13). Unfortunately, despite a growing body of literature on green buildings and increased policy attention, adoption of green building practices across the globe continues to be inconsistent because of financial barriers, lack of technical capacity, and weak institutions, particularly in developing countries[9].

1.2 Net-Zero 2050 Transition and Sarawak Context

Achieving net-zero emissions by 2050 is a major structural change to the energy system, building system, and the urban development system around the world. Net-zero means that we are able to balance emission sources with what we remove through various mitigation strategies like increased energy efficiency, using renewable energy, and developing carbon reducing technologies.

One of the sectors where significant progress can be made toward a global transition to a low carbon future is in the building sector. The IEA (2023) anticipates that achieving global net-zero pathways as set out under current climate agreement targets will require annual reductions in building-related emissions of more than 9% between now and 2030[10]. Therefore, this transition will necessitate a rapid decarbonisation of the building sector.

Malaysia has committed to achieving net-zero emissions by 2050, supported by national strategies such as the National Energy Transition Roadmap (NETR). However, translating these commitments into the building sector remains challenging due to fragmented implementation and limited enforcement of low-carbon requirements in construction practices[11].

The transition to renewable energy sources is occurring throughout the world. Sarawak generates a significant percentage of Malaysia's electricity and is mostly supplied by hydroelectric power, making it one of the most renewable energy-rich areas. However, the adoption of green buildings in Sarawak has only recently begun and only to a small extent; therefore, there are limited examples of building methods based on zero-net energy designs or similar principles that have been adopted by the general construction industry[12].

Sarawak's tropical climate produces a hot, moist environment with an abundance of rainfall that creates a high demand for cooling energy and a corresponding increase in energy use for building operation. The high availability of renewable energy further creates the opportunity for low-carbon building development in this area[13]. However, existing studies identify persistent barriers including high upfront costs, limited technical expertise, weak performance monitoring, and insufficient financial incentives[14, 15]. More importantly, the absence of localized lifecycle carbon data and limited empirical evidence on net-zero readiness in Sarawak creates a critical knowledge gap in guiding policy and implementation strategies.

1.3 Research Scope, Conceptual Focus, and Objectives

This investigation examines the development of green buildings in Sarawak as part of a wider picture of sustainable development and net-zero transition strategies. In addition to qualitative thematic synthesis, the study incorporates quantitative descriptive analysis of publication trends, thematic distributions, and geographical characteristics of the reviewed literature to provide a broader evidence-based overview. The synthesis of the literature related to policies, technologies, finance, and institutions helps to understand the level of preparedness in the construction industry to identify the future strategic pathways for decarbonising the built environment[16]. Using a multi-dimensional, socially and technical, integrated framework has guided the study's understanding of how important drivers and barriers, enablers, social and technical outcomes are connected within long term net-zero transition pathways. Aspects include drivers such as policy pressures, growing energy demands and sustainability goals; and barriers to implementation: financial, technical, institutional. Technological innovation, financial mechanisms, governance systems, collaborative efforts among multiple stakeholders, and human capital are all enabling factors that help with the transition. In turn, these enable a variety of successful outcomes from the transition, including, increased adoption of Green Buildings; improved energy efficiency; and reduction of carbon emissions. Thus, we conceptualised Green Building Development as a multi-level socio-technical transition rather than simply a technical solution[17].

Green building support policies; energy-efficient design; renewable energy integration; lifecycle carbon assessment; financial mechanisms; stakeholder coordination; and capacity building systems are the major areas of focus within this research project related to the construction sector in Sarawak. Through this scope, the study evaluates current developments, implementation challenges, and opportunities for accelerating the transition toward a low-carbon and net-zero built environment. This research contributes to existing knowledge by producing a systematic understanding of the processes of transition to green buildings within tropical developing climates, specifically focusing on the sociotechnical dimensions and policy context within Sarawak. Additionally, this study identifies important gaps that need attention with respect to lifecycle carbon counting and local data availability, and implementation readiness, as they are necessary for evidence-based policymaking and for future research on this topic.

1.4 Objectives

The objectives of this study are:

1. To examine the current status and adoption trends of green buildings in Sarawak.
2. To identify key drivers, barriers, and enabling conditions influencing implementation.
3. To evaluate sustainable design strategies and low-carbon technological solutions.
4. To assess financial, institutional, and human capital readiness for green building adoption.
5. To propose strategic pathways for achieving net-zero buildings in Sarawak by 2050.

This research adds to existing knowledge by providing a structured approach to green building transitions in tropical developing countries, with attention to the specific socio-technical and policy issues relevant to Sarawak. It also identifies shortcomings in carbon accounting through the lifecycle of a building, availability of local data and readiness for implementing green construction practices, which are important for evidence-based public policy development. Figure 1 illustrates a conceptual model of the built environment's transition to net-zero emissions through the interaction of various factors, including policy drivers, energy demand, and sustainability targets, in addition to financial, technological, institutional barriers, and incentives that impact green building operation, energy-efficient buildings, and carbon reduction.

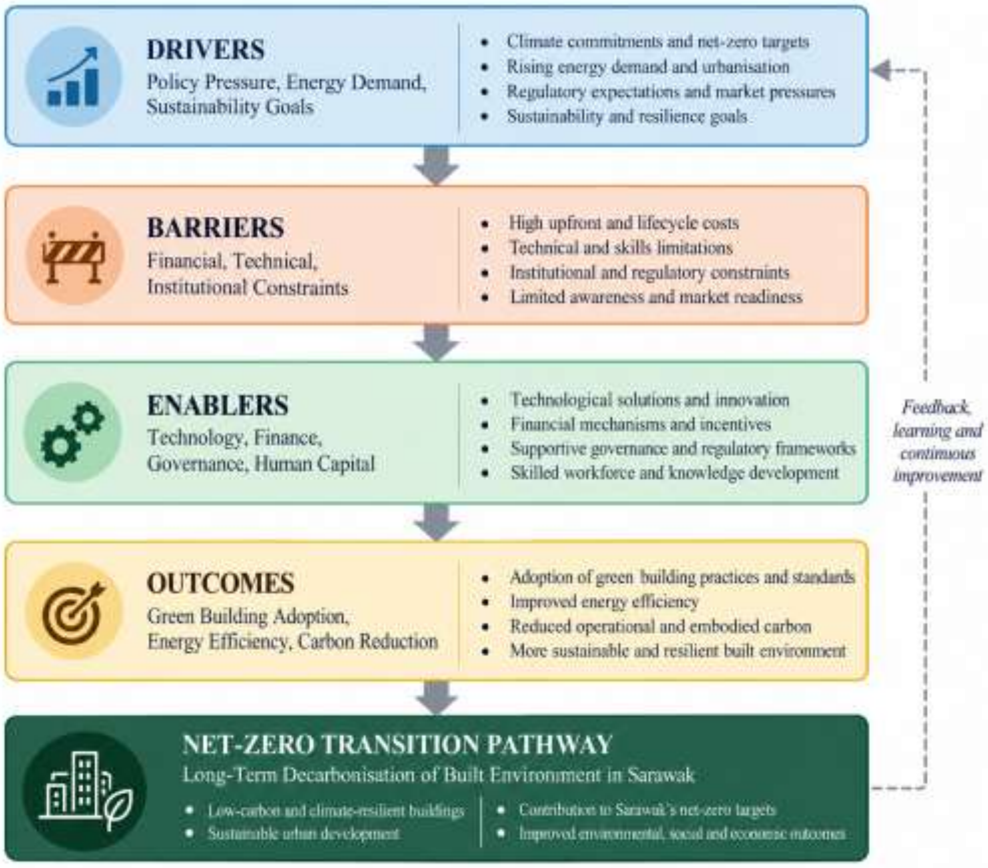

Figure 1. Conceptual Framework for Green Building Adoption and Net-Zero Transition Pathways in Sarawak.

2. METHODOLOGY

This study utilised a structured narrative review, informed by PRISMA guidelines, including qualitative thematic synthesis and quantitative descriptive content analysis. The qualitative component identified key drivers, barriers, enablers and pathways for transition to developing Green and Net Zero buildings, while the quantitative component examined thematic frequency, distribution, trends in publishing and areas of focus in research found in the literature selected. This method provides a structured but flexible way to evaluate the development of green and net-zero buildings and will focus on their application in Sarawak, Malaysia. The PRISMA-based method allows for greater transparency in the process of selecting literature while still allowing for the selection of literature that is appropriate for interdisciplinary sustainability research; there is great diversity in terms of the methods used.

2.1 Literature Search Strategy

A structured literature search from 2010 to 2025 was performed across Scopus, Web of Science, ScienceDirect, and Google Scholar to locate studies. Search terms were "green buildings," "sustainable buildings," "net zero buildings/net zero carbon buildings," "energy efficiency," "embodied carbon," "life cycle assessment," "renewable energy integration," "smart buildings," "building information modelling (BIM)," "barriers to green building," "policy frameworks," "Malaysia," and "Sarawak." Grey literature was also sourced for policy and industry perspectives using reports and guidelines by IEA, UNEP, IFC, World, GBI Malaysia, and ISO standards.

2.2 Study Selection Criteria

The selection of studies was undertaken based on the following predetermined inclusion and exclusion criteria established beforehand to ensure quality and relevance.

2.2.1 Inclusion criteria:

Studies were included if they met the following criteria:

1. **Publication type:** Peer-reviewed journal articles, conference proceedings, and relevant institutional, governmental, or technical reports addressing the review topic.

2. **Building focus:** Studies examining green buildings, net-zero energy buildings, net-zero carbon buildings, sustainable buildings, or related low-carbon building transitions.

3. **Technical and environmental dimensions:** Studies addressing one or more of the following: energy efficiency, renewable energy integration, lifecycle assessment, embodied carbon, operational carbon, or other building-related decarbonisation strategies.

4. **Policy and implementation dimensions:** Studies examining policy and regulatory frameworks, financial mechanisms, governance arrangements, stakeholder dynamics, or other institutional factors influencing the development, adoption, or implementation of sustainable and low-carbon buildings.

5. **Geographical relevance:** Studies addressing the global context, national contexts, or specific contexts relevant to Malaysia and Sarawak, including studies that provide transferable insights into tropical developing-country settings.

6. **Relevance to the review objective:** Studies providing substantive evidence or conceptual insights relevant to understanding the transition from green building practices towards net-zero buildings.

2.2.2 Exclusion criteria:

- Studies were excluded if they met any of the following criteria:

1. **Scope:** Studies unrelated to the built environment, building sector, construction industry, or building-level sustainability and decarbonisation.

2. **Insufficient research contribution:** Articles lacking a clearly described research methodology, substantive theoretical contribution, or empirical evidence relevant to the review objectives.

3. **Publication duplication:** Duplicate records or multiple records reporting substantially the same study, with the most complete or relevant version retained.

4. **Language and accessibility:** Publications not available in English or for which the full text was not accessible in a searchable format.

5. **Topic relevance:** Studies with insufficient relevance to green buildings, energy efficiency, renewable energy integration, sustainable construction, carbon reduction, or the transition towards net-zero buildings.

2.3 Screening and Selection Process (PRISMA-Informed)

The screening and selection process followed a PRISMA-informed approach and comprised three sequential stages:

1. **Identification:** Relevant literature was identified through systematic database searches using predefined search terms and, where appropriate, supplementary citation tracking of relevant publications. Retrieved records were compiled and screened for duplicate entries.

2. **Screening:** Titles and abstracts were screened against the predefined inclusion and exclusion criteria to remove duplicate records and studies that were clearly outside the scope of the review.

3. **Eligibility:** The full texts of potentially relevant studies were assessed against the inclusion and exclusion criteria. Studies were retained where they provided substantive evidence or conceptual insights relevant to green buildings, energy efficiency, renewable energy integration, sustainable construction, carbon reduction, or the transition towards net-zero buildings.

The three levels of filtering described above were intended to only include those studies with direct relevance to the research question and conceptual model reflected in the final synthesis as shown in Figure 2.

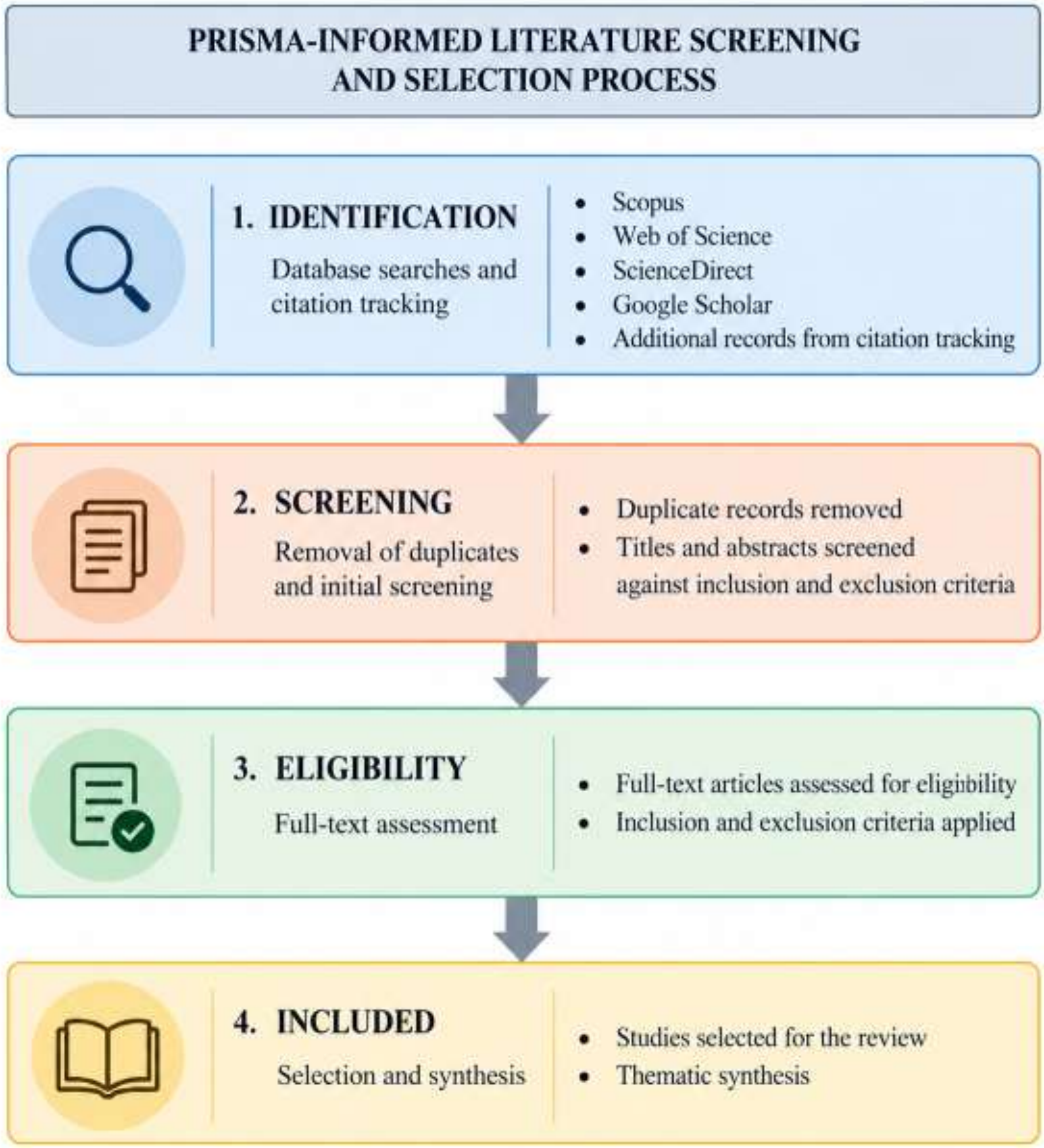

Figure 2. PRISMA-Informed Flow Diagram Illustrating the Literature Identification, Screening, Eligibility Assessment, and Inclusion Process.

2.4 Data Extraction and Thematic Synthesis

Key analytical dimensions were used to categorize and extract data from the experiments and studies performed on all selected projects including:

- Design of building and energy performance strategies
- Renewable Energy Sources/Smart Building Technology
- Embodied Carbon/Lifecycle Assessments
- Economic Viability/Lifecycle Costs
- Policy/Governance Frameworks

- Organizational and Stakeholder Readiness for Sustainable Buildings
- Barriers/Facilitators of Green Building Certification
- Pathways Toward Net-Zero Transition.

A thematic synthesis approach was used to identify patterns, relationships, and contradictions across studies. Themes were iteratively refined through comparison across developed and developing country contexts, with emphasis on tropical climate relevance to Sarawak. In addition to the qualitative thematic synthesis, a quantitative content analysis was performed to determine the frequency of occurrence of the major themes within the reviewed literature. The studies selected for the analysis were coded based on defined qualitative analytical dimensions such as policy frameworks, technical solutions, financial mechanisms, stakeholder involvement, lifecycle assessment, integration of renewable energy, and barriers to implementation. Descriptive statistics were then used to summarize the frequency and distribution of the identified themes. In this way, the quantitative analysis provides a summary of the dominant trends in research as well as the areas of research priority in the literature pertaining to green buildings and the transition towards net-zero buildings.

2.5 Data Analysis and Interpretation

The synthesis of this research was performed using a conceptual framework that outlined a logical structure of how the drivers, determined by technology, institutions, financing, and behavior, interact with barriers and enablers to influence implementation outcomes and ultimately the net-zero transition pathways. In addition, the findings were further contextualized by the ecological and socioeconomic conditions of Sarawak to assess the prospects for transitioning from conventional buildings towards net-zero buildings by 2050.

To complement the qualitative synthesis, descriptive statistical analysis was conducted on the selected studies. This analysis examined the number of papers published on green building research over different time periods, the publication sources, the types of methodologies used, and the frequency with which the different green building research themes were reported. The results of this analysis were illustrated through graphs and tables to demonstrate the distribution and changes of key green building research themes during the time period of 2010 to 2025. The included studies had different research designs, data sources, and outcome measures; statistical meta-analysis was not performed.

This hybrid approach combined qualitative thematic analysis and quantitative descriptive analysis that resulted in an in-depth understanding of the factors influencing the adoption of green buildings and the potential to achieve net-zero buildings in Sarawak.

2.6 Reliability and Validity Considerations

Triangulation, or the use of the data from multiple sources, including peer-reviewed articles, international reports and documents was used to provide increased reliability. By using both global and Malaysian studies, context is balanced and geographic bias is reduced. In this study Descriptive Quantitative Content Analysis was employed by examining publication trend distributions, thematic distribution, and characteristics of publications. The use of a PRISMA-informed structure will provide clarity and transparency in the process of identifying, screening and selecting literature. Moreover, the combination of qualitative thematic synthesis and descriptive quantitative analysis will create more methodological rigour, reproducibility, and comprehensiveness in conducting the combined analysis providing comprehensive data to better understand green building developments and net-zero transition pathways in Sarawak.

2.7 Overview of Reviewed Literature

Around 300 publications were reviewed for this study, including peer-reviewed articles, conference papers, government and industry reports, and other relevant materials. An analysis of the literature identified a marked increase in research interest in green buildings and net-zero transitions after 2020, with the most common topics focusing on technology, energy efficiency, and renewable energy.Research activity related to green building, sustainable construction, and net-zero development increased substantially after 2020 (Table 1). This increase corresponds with the growing global focus on decarbonisation strategies, energy efficiency, and climate change-related policy initiatives associated with international net-zero commitments and the United Nations 2030 Agenda for Sustainable Development Goals.

Table 1. Distribution of Reviewed Literature by Publication Period

Publication Period	Number of Studies (n)	Percentage (%)
2010–2015	45	15.0
2016–2020	105	35.0
2021–2025	150	50.0
Total	300	100

The above description provides an overview of the geographical distribution of the literature reviewed (Table 2). The studies reviewed are mainly a blend of international/global view and an Asia Pacific and Malaysian continent/region-focused view. The resulting geographic distributions give a good general global or international understanding of best practices, while providing local context in Malaysia and Sarawak. The use of literature from multiple regions of the world improves comparative analysis of policy frameworks, technology usage and implementation challenges.

Table 2. Geographic Distribution of Reviewed Literature

Region	Number of Studies (n)	Percentage (%)
Global/International	90	30.0
Asia-Pacific	75	25.0
Malaysia	45	15.0
Southeast Asia	30	10.0
Europe	36	12.0
North America	24	8.0
Total	300	100

According to Table 3, the most frequently cited research themes found in the literature review were energy efficiency, building design and modelling, renewable energy integration, and policy frameworks, all of which are considered to be important themes in regards to green building development as well as achieving net-zero. However, there were some areas of research with less attention; thereby indicating that such areas include stakeholder readiness, smart building technologies, and long-term implementation pathways for net-zero.

Table 3. Major Themes Identified in the Reviewed Literature

Theme	Number of Studies (n)	Percentage (%)
Energy Efficiency and Building Design	225	75.0
Renewable Energy Integration	195	65.0

Theme	Number of Studies (n)	Percentage (%)
Policy and Governance	180	60.0
Lifecycle Assessment and Embodied Carbon	165	55.0
Financial Mechanisms and Lifecycle Costing	135	45.0
Stakeholder Readiness and Capacity Building	120	40.0
Smart Buildings and Digital Technologies	105	35.0
Net-Zero Transition Strategies	90	30.0

3. CONCEPTUAL FRAMEWORK FOR NET-ZERO BUILDING TRANSITION IN SARAWAK

The research framework conceptualizes the transition to green and net-zero buildings as a multidimensional system shaped by the interactions among policy, technology, finance, and key stakeholders. The framework does not look at the adoption of green buildings as a technically focused process; instead, it looks at how the adoption of green buildings is influenced by the governance systems in place, the market conditions that exist, the degree of technology readiness, and the human factors that are impacting the adoption of green buildings.

Sustainability transition theory and socio-technical systems thinking are the foundational components of the framework. They support the notion that low-carbon transitions result from aligning technology (innovation), institutions (rules), finance (mechanism) and people (actors). In the context of Sarawak, this integrated approach is valuable because of the combination of abundant renewable energy potential and very limited capacity to implement green buildings. Furthermore, the development of this framework is further informed through a quantitative descriptive analysis of the existing literature that was included in the review. Most of these studies examined policy, technology, finance or stakeholders.

3.1 Core Components of the Framework

3.1.1 Policy Dimension

Foundational to the overall framework that will define the speed and direction of green building is the policy. Policies are typically framed at both the national level (large scale) and at the local/state level (mid-size scale) through regulations for energy efficiency, regulations for building code, sustainability master plans, and through green certification systems. In Malaysia and Sarawak, there are several policy instruments, such as NETR, MS 1525 energy standards and GBI, that provide guidance, but they are still not mandatory and can lead to disparity between policy intent and the actual results from adopting policies.

From the perspective of being an effective market-shaping influence on how developers behave, on investment decisions, and on compliance levels throughout the green building industry, there is a clear indication from the descriptive literature analysis that policy and governance are included as themes in almost all studies reviewed that support that policies and governance are key to enabling green building adoption.

3.1.2 Technology Dimension

As the operational enabler of net-zero and green buildings, technology includes energy-efficient systems, renewable energy integration and passive design strategies as well as low-carbon materials and smart building technologies. Technological solutions such as Building Integrated Photovoltaics (BIPV), high-performance building envelopes, Internet of Thing (IoT) based energy monitoring systems and lifecycle assessment tools provide direct influence over how well buildings perform.

Technological effectiveness can be dependent upon (1) the context of the application, for example; the need for cooling load reduction and humidity control through passive ventilation within Sarawak's tropical climate, and (2) that failure in the effective integration or implementation of technology can lead to a considerable reduction in expected energy savings, and therefore, highlights the need for optimization during the design phase. The quantitative thematic distribution of the literature demonstrates that technology and energy efficiency are leading topics within current research and will continue to be the dominant area of research until proven otherwise.

3.1.3 Finance Dimension

Project-level implementation or rejection of green building solutions comes down to financing. Even though long-term lifecycle costs can be saved through green building construction, the initial investment is generally higher than traditional construction (15% to 20% higher). In order to bridge the initial cost barrier, financial mechanisms such as green bonds, ESG investment frameworks, energy performance contracting, and government incentives are needed. Through lifecycle costing analysis, operational savings can often exceed the initial investment over time. However, short-term financial decision making is still a significant barrier in developing countries. Access to dedicated green financing mechanisms is limited in the state of Sarawak. This is a stumbling block to the adoption of green building practices by private developers and by small to medium-sized contractors. While financial mechanisms have an important role in facilitating the implementation of green building practices on a large scale, they have not yet been explored in great detail within the literature.

3.1.4 Stakeholder Dimension

The frameworks of the stakeholder's layer is a social and organisational one, which includes developers, government agencies, contractors, consultants, financial organisations, end-users, and academic organisations. How well these groups work with each other determines how well the policies are enforced, how well technology is adopted, and how well finances are implemented. Poor coordination among stakeholders can lead to fragmented decision making, inefficiently designed products, and a loss of value in sustainability through construction.

In contrast, strong stakeholder integration particularly early-stage collaboration between designers, engineers, and policymakers has been shown to significantly improve sustainability performance and reduce project inefficiencies.

In Sarawak, the limited technical capabilities of stakeholders and varying degrees of understanding are two significant barriers to the adoption of green buildings. Also, there are few references to coordinating stakeholders or developing their capabilities, showing a disconnect between creating a technical solution and preparing to implement that solution.

3.2 Integrated System Interaction (Policy–Technology–Finance–Stakeholders)

The four portions are not separate from one another. Rather, they all work together to form a larger overall structure, which can also be noted in the way the various types of research on the subject are categorized.

- Policy drives technology adoption through regulations and standards.
- Finance enables technology implementation by reducing investment barriers.
- Stakeholders mediate policy and finance into action through decision-making and project execution.
- Technology determines final environmental performance outcomes, including energy efficiency, carbon reduction, and lifecycle sustainability.

The failure of any one dimension creates systemic inefficiencies. No financial support for a strong policy limits the ability to adopt it, whereas, if there is significant technological advancement without a skill set within stakeholders, then enormous variance occurs with the difference between how a technology performs according to the design versus what it performs according to reality.

3.3 Outcome Pathway: Toward Net-Zero Buildings in Sarawak

The interaction of the four dimensions leads to three key sustainability outcomes:

1. **The adoption of Green Buildng:** The initial introduction of energy-efficient and sustainable design methods through building development.
2. **Reduction of the Carbon from Building Operations:** The improvement in energy performance and the reduction of carbon emissions produced by a building during its operational stage.
3. **Net-Zero Transition:** long-term alignment of operational and embodied carbon reduction strategies

At the present time, Sarawak is still in the early stages of adopting the transition pathway and the overall results will only consist of partial implementation of green buildings, rather than a complete implementation of net zero performance. The overall results of the reviewed studies will remain consistent with the trends of publication and the thematic variance in reviewing the studies.

4. GREEN BUILDING CONCEPTS AND POLICY CONTEXT

4.1 Green Building Concepts and Sustainability Principles

The goal of a Green Building is to decrease the negative environmental effects of building design, construction, operation and maintenance while increasing resource efficiency, health and wellness of building occupants, and long-term building performance through the life cycle of the building. On the other hand, traditional buildings are designed, constructed, operated and maintained without regard to how these aspects will affect each other when considering the entire life cycle of the building, and do not include concerns about Environmental, Social and Economic Sustainability, as required for Sustainable Development and Life Cycle cost estimate methodology[18, 19]. The increasing emphasis on constructing green buildings is directly related to the substantial environmental impact of the built world. The construction industry is still one of the largest users of energy and produces major quantities of greenhouse gases, thereby making it necessary to develop low-carbon or resource-efficient development options. Therefore, green building techniques are intended to decrease operational energy usage, increase water efficiency, reduce the amount of waste produced, increase indoor air quality, and reduce the embodied carbon associated with the use of construction materials and building methods. Green Buildings are being documented as a social-technical transition, not just a technological one. The ability to achieve "meaningful" sustainability goals will require a relationship between technology, policy, finance and stakeholder engagement. Therefore, Green Buildings are now deemed to be an important vehicle for climate mitigation, urban sustainability, and Tier 2 Resilience goals in developed and developing economies alike. This conclusion is supported through a descriptive quantitative analysis of the literature reviewed, which demonstrates how energy related issues, policy related issues (including legislation/policies) and technologies are the most prominent areas of focus in green building research[20]. Sustainable building development throughout Malaysia is backed by national standards for energy efficiency, as well as by policies concerned with the environment, which promote resource-efficient design and operation of buildings. These programs assist with improved building performance and, in turn, help to achieve the nation's larger goals of low carbon development and net zero emissions[21]. Green building principles and the performance impacts associated with them have been reviewed in prior literatures and are discussed in Table 4 below. The largest proportion of energy savings can be achieved with energy efficiency and passive design strategies; therefore, these principles are integral to reducing the operational energy demand of the building. Additionally, low-carbon materials and water conservation measures will contribute significantly to the overall sustainability performance of the building. These results validate that integrated design approaches are required to achieve the sustainability goals of the building.

Table 4: Core Green Building Principles and Reported Performance Impacts from Literature

Principle	Description	Impact	Reference
Energy efficiency	Passive and active strategies to reduce operational energy consumption through efficient HVAC, lighting, controls, and building design	6.7–66.2% energy savings	[22]
Passive design	Building orientation, envelope optimization, shading, insulation, and natural ventilation to minimize energy demand	20–60% energy reduction	[23]
Water conservation	Low-flow fixtures, rainwater harvesting, and greywater recycling systems to reduce potable water use	30–50% water savings	[24]
Low-carbon materials	Use of alternative cementitious materials, recycled content, and low-embodied-carbon construction products	30–70% CO_2 reduction	[25]
Green buildings overall	Integrated design approach combining energy, water, material, and environmental performance strategies	20–50% energy reduction	[26]

4.2 Green Building Standards and Certification Systems

Certification systems for buildings help translate sustainability principles into usable performance measures. Certification systems establish organized evaluations of how well buildings perform environmentally, create incentives for improving environmentally responsible practices, and enable the comparison of buildings' sustainable accomplishments among members of the building community.

The GBI is Malaysia's main national green building rating system. The GBI was created by PAM (Malaysian Institute of Architects) and ACEM (Association of Consulting Engineers Malaysia) and evaluates all aspects of sustainability for a building: energy efficiency, indoor environment, sustainable site design, water usage, materials and resources, and innovative design. GBI offers different levels of certification, including Certified, Silver, Gold and Platinum, which reflect how sustainable a building is depending on the rating[27].

In addition to GBI, other assessment methods such as GreenRE and MyCREST have been implemented to create sustainable development through the use of performance-based evaluation. International certification systems such as LEED, BREEAM and EDGE have also been implemented in a number of Malaysian projects where multinational companies are involved in development or where international commitments to sustainability exist[27, 28].

The certification standards and frameworks referred to above are also supported by Malaysia Standard MS 1525 (Technical Guideline for the Design and Operation of Energy Efficient Buildings). In combination with the above certifications and standards, this certification framework provides the basis for improved building performance and increased market confidence in the use of sustainable construction practices[29]. A descriptive analysis of the literature reviewed identified certification and policy instruments as the most frequently identified and cited enablers of green building adoption around the world.

4.3 Policy and Governance Frameworks in Malaysia and Sarawak

Malaysia's shift to more sustainable and lower carbon forms of development is being supported through a range of Federal policy initiatives and strategies that include the following: National Policy on Green Technology, the Master Plan for Green Technology Implementation; National Energy Policy; and NETR. Together, these frameworks aim to enhance energy efficiency, enhance renewable energy generation and reduce greenhouse gas emissions from all major economic sectors, including the built environment[30].

Green building certifications may be largely impositional and thus the resulting implementations take place in larger urban locations; thus making the overall rate of adoption relatively poor across different regions generally as a result of incentives[31].

Because of its many renewable energy resources particularly hydropower, and urban development, Sarawak has a position of strategic importance in the way that it will contribute to the development of sustainable energy in Malaysia. Sarawak's Energy Profile also offers an excellent opportunity for the integration of energy-efficient buildings and future development projects to pursue net-zero[32].

Currently Sarawak is just starting out with implementing green building practices. However, there are many barriers that still exist. In addition, these barriers may be due to limited technical knowledge; high initial capital investment cost; inadequate means to monitor performance; lack of coordination among stakeholders; and a complete absence of a local framework that has been developed to suit the specific environmental, economic, and institutional context of Sarawak. Thus, having access to policies alone does not allow for accelerating the adoption of sustainable (green) buildings. Instead, it is necessary to develop an environment where there are effective ways of coordinating and providing support at the institutional level; there are stronger regulations; there is a better capacity within the industry; and there is a closer alignment between governmental policy goals and market-based incentives[33].

Hence, Sarawak's shift towards net-zero buildings needs to be seen as a cross-sectoral challenge, with policies, technology, financing, and engagement from stakeholders all at stake. This point of view is the primary anchor of the conceptual framework that was used in this study, and it serves as the basis for analysing the drivers, barriers, and pathways to transition that will discussed in following sections. These findings conform to the same thematic distribution of the literature that has been reviewed, which indicates comparatively less focus on regional implementation studies, despite a very strong global policy discussion.

5. DRIVERS, BARRIERS, AND ADOPTION STATUS IN SARAWAK

5.1 Adoption Trends and Market Readiness

In Sarawak, green building development is still in the early stages of maturity and developing rapidly despite growing political focus and awareness around sustainability policies. This opinion has been substantiated by a quantitative analysis based upon the literature reviewed, showing much less emphasis placed on research focused on green building adoption; in fact most research projects have focused either on green building technologies or policy-related issues. Construction stakeholders generally acknowledge and support sustainable construction principles, although the implementation of these principles into projects is only limited and has demonstrated a gap between sustainability awareness and actual implementation [34]. The same pattern is evident in the case of Malaysia, where sustainability initiatives have been put in place; however, the level of green construction still lags behind that of other developed countries[35].

Perceptions about cost, investment risk and demand uncertainty greatly influence the market readiness of green buildings. The typical first cost excess for green buildings ranges from 5-15% over traditional development. This is mainly due to enhanced design requirements, the use of advanced technologies as well as the cost of certification. However, these extra initial costs are frequently offset through long-term operational savings and improved building performance. Internationally, it has been established that green buildings achieve 20-30% in lifecycle cost savings, as well as significant reductions in both energy and water consumption[36].

In terms of reaching sustainable construction in Sarawak, recent developments indicate a progressive improvement in readiness to undertake sustainable construction through government initiatives and the increasing awareness of sustainability (including their growing adoption of certification systems like the GBI. This represents a strengthening of the institutional support available. Despite this strengthening support, there is limited market penetration of sustainable design, especially for private-sector developments, where the investor has continued to make decisions based mainly on short-term economic benefits for the past several decades. These results also match the patterns in the literature reviewed, which indicate that the main research domains of energy efficiency, policies, and technological solutions are all well represented in this area.

5.2 Economic and Financial Drivers

The economic realities of an area have a major impact in determining if Green Building can ever become successful. Long-term sustainability tends to require increased up-front costs. However, many studies demonstrate how Sustainable buildings provide long-term financial return on investment when looked over the life cycle of the building through lifecycle cost (LCC) analysis which identifies total building costs associated with designing, constructing, operating, maintaining and disassembling the building and much better represents the value of a project than measuring only initial capital cost[37].

According to studies, around 60%-80% of total lifecycle cost will be made up of operational costs; while only making up 20%-40% of initial construction cost[38]. As a result, the implementation of energy-efficient systems, water conservation methods, and sustainable building technologies can provide significant long-term savings. Research shows that green buildings realize 20%-30% less in lifecycle costs and have an estimated energy savings of 25%-50% compared to conventional buildings[39].

Access to green finance has the potential to further encourage widespread adoption of products in the marketplace. Access to various financial instruments (green bonds, sustainability-linked loans, climate funds, and ESG investments) are supporting the growth of sustainable building products globally. In many cases, green building-certified buildings can achieve higher asset values and be more marketable and command rental premiums compared to traditional buildings[40]. However, many developing countries do not have access to financing in order to invest in sustainable technologies or upgrades on their buildings. The quantitative descriptive analysis of the studies reviewed further substantiates the prominence of economic and technological factors in the decision-making processes of building owners around the adoption of green building products.

5.3 Organizational Readiness and StakeholderRoles

Implementation of green buildings is contingent upon a variety of factors including the technologies available; the financing resources needed; the organizational readiness of the owner/developer; and the commitment of all stakeholders involved in the project. Companies with effective sustainability leadership have a greater propensity to integrate eco-friendly objectives in planning for projects; provide resources for new initiatives related to sustainability; and create governance structures to support development that meets sustainable principles[41].

The green building ecosystem in Sarawak entails many different stakeholder groups, such as: government agencies, developers of all types (including financial institutions), consultants and contractor groups, utility providers, academic institutions, for-profit organizations, and others. Government agencies are responsible for formulating policies around green building practices, approving plans developed by those involved in these types of projects, and providing appropriate regulatory guidance to create a smooth process through which green building can occur; likewise, developers and building owners are the primary decision-makers that influence project adoption on a project-by-project basis[42].

Experts and contractors provide valuable skills outside of those two areas, as well as contribute to the design and building process; however, the large, high level of inexperience with advanced green building products poses a serious problem. Access to capital is also the major factor affecting project feasibility by financial institutions, while both universities and research centres can help create knowledge and innovation to develop new jobs. Ultimately, the ability to successfully implement green building practices depends on the level of collaboration and coordination between the various stakeholders throughout the entire construction process [43].

Using formal sustainability governance structures in organizations has been associated with enhanced project outcomes and reduced inefficiencies, as well as improved environmental performance, due to better accountability, improved alignment of strategy with operational plans, and coordinated decision-making processes[44]. The lack of effective institutional support, divided decision-making, and resistance to making changes within an organization can significantly hinder successful sustainability efforts and make it more difficult for an organization to fully integrate sustainability into its operations [45]. There are fewer references to stakeholder-related themes in the literature reviewed versus references to technical solutions, indicating a disparity between technical solutions versus organizational implementation capabilities.

5.4 Human Capital and Capacity Building

The ability to develop human capital will allow for an increase in the use of green buildings. The development of the environment requires a mix of different types of experts in the fields of architecture, engineering, energy use analysis, lifecycle analysis, environmental management and integration with renewable energy. In many developing parts of the world such as Malaysia, there is an ongoing shortage of skilled workers.[46].

Objective Studies show that a substantial percentage of workers in the construction industry do not possess adequate knowledge or training with respect to sustainable practices, which presents a hindrance to effectively implementing green technologies, energy efficiency systems and meeting the requirements for green building certifications. [47]. Projects can be made much better with help from green-certified professionals and sustainability experts, who have the skills to do this with improved design integration, better environmental management and improved building performance over the course of the entire life of the project[48].

For these reasons, developing capacity building programs; creating professional certification programs; delivering industry training; and providing sustainability-focused education through universities are key to supporting long-term, transformative changes within the industry in the future. In Sarawak, working together among academia, professional institutes and industry stakeholders in the area of increasing technical skill and knowledge will be very important to create sufficient capacity to deliver continued growth in sustainable construction in the years to come.

5.5 Urban, Rural, and Climate Contexts

The implementation of green buildings in Sarawak is significantly impacted by the geography and climate of the state. Rapidly developing urban areas like Kuching, Miri and Bintulu are present and are interspersed throughout regions of rural or remote areas with different levels of infrastructure development[49].

Because they are able to use advanced technologies, financing, qualified professionals, and regulatory enforcement methods, urban areas usually have more facilities than rural sites that are willing to embrace green building. Rural areas face challenges with limited access to technical expertise, more expensive trucking, and limited access to sustainable building materials, causing rural areas to have lower rates of adoption[50].

In terms of climate, Sarawak is characterized by a hot, humid equatorial tropical climate with high temperatures and high humidity (up to 90%). With these high climatic conditions, cooling demand in Sarawak has increased, resulting in pressure on building energy use and consumption and therefore an increased demand for passive design methods such as natural ventilation, solar shading, daylight optimization and the use of high-performance building envelopes to help improve building performance locally[51].

At the same time, Sarawak possesses considerable renewable energy potential, particularly through hydropower and solar resources. These advantages provide opportunities to support low-carbon building development and contribute to Malaysia's broader decarbonization objectives[52].

5.6 Barriers to Green Building Implementation

Even though people know more about green building and have an increased amount of policies available to them, many things continue to hinder the more widespread use of it in Sarawak. One of the most commonly cited was the barrier of financial constraints perception of higher initial costs/longer investment returns; there are few options available for green financing, which makes this even more difficult to surmount[53].

Lack of skilled workers, no knowledge of sustainable design methods, and not having the necessary special tools for assessing sustainability are examples of some technical barriers. The supply chain presents the same type of technical challenges: increasing costs and reducing the efficiency of the implementation of your project through the limited availability of certified sustainable products and low-carbon technologies[54].

Policy and regulatory challenges are affecting adoption as well. Malaysia has developed multiple policies for sustainability, as well as some certification systems, but they have yet to develop formal policies for enforcing these policies; therefore, enforcement is typically done voluntarily. Other impediments to progress are also poor stakeholder awareness; lack of data on the environment; and little cooperation between the various participants in industry[55].

These barriers highlight the need for integrated strategies that combine regulatory support, financial incentives, capacity development, technological innovation, and stakeholder collaboration to accelerate green building adoption across the state[56]. This corroborates the quantitative thematic distribution indicating that Financial&Technical barriers have been identified as two of the most common barriers by the literature.

5.7 Synthesis

Sarawak has shown a lot of progress in green and net zero buildings in a relatively short time frame but is still currently in the early phases of transitioning to these types of buildings. The current reason for adopting green and net zero buildings has primarily been due to the help of governmental policies, concerns for the environment, advancements in technology and emerging market opportunities. Despite all the reasons listed above, there are still many financial barriers, technical capabilities, insufficient policy enforcement, supply chain issues and insufficient stakeholder awareness that continue to impede the transition process. Through cooperation of all stakeholders to implement policy interventions, build capacity through technical training and education, build green financing mechanisms and improve collaboration - the rate of transition to a sustainable and net zero built environment will increase significantly by 2050.

Table 5 describes how the adoption of green buildings in Sarawak is impacted by various drivers and barriers. The primary drivers of adopting sustainable buildings are related to economics and policy. Conversely, the barriers impacting adoption include a lack of financial resources and a lack of technical capacity. It will be important that development of these types of policies, financial incentives and capacity building strategies work together to create a conducive environment for increasing the number of sustainable buildings.

Table 5. Key Drivers and Barriers to Green Building Adoption in Sarawak Based on Reviewed Literature

Dimension	Drivers	Barriers	Reference
Policy	NETR, state sustainability initiatives, public procurement requirements	Weak enforcement, voluntary certification, fragmented governance	[57]
Economic	Lifecycle cost savings, higher asset value, energy cost reduction	High upfront costs, limited green financing	[58]
Environmental	Climate change mitigation, energy efficiency needs, carbon reduction goals	Limited awareness of environmental benefits	[41]
Technology	Renewable energy, BIM, smart building systems	Skills shortages, technology integration challenges	[59]
Supply Chain	Growing availability of green products	Material shortages, import dependence, lack of carbon databases	[60]
Stakeholders	Increasing collaboration and institutional support	Weak coordination, resistance to change, limited market demand	[61]

6. GREEN TECHNOLOGIES AND SUSTAINABLE STRATEGIES

6.1 Passive Design and Energy Efficiency

Energy efficiency is widely recognized as the first and most cost-effective step toward sustainable and net-zero buildings. Consequently, active and passive energy efficient designs measures form the foundation of green building development by minimizing reliance on mechanical systems while improving occupant comfort and reducing operational carbon emissions[62]. These practices have even higher value in tropical areas of the world, such as Sarawak, where high temperatures and humidity result in significant cooling energy demand. Therefore, energy requirements for cooling are very substantial.

Using passive design tactics like proper building orientation, utilising daylight, high performance thermal envelope, natural ventilation, and solar shading can drastically decrease the amount of heat absorbed by buildings, leading to reduced energy demand and consumption. Properly orienting a structure and designing its façade can greatly inhibit the absorption of solar heat and lower the cooling loads created by the building; if you use solar shading devices such as overhangs or horizontal or vertical louvres, the estimated savings on cooling energy are typically in the range of 20-30%, Natural ventilation strategies have also been shown to reduce cooling energy requirements by 20-40%, depending on building configuration, location, and climate[63, 64]. High-performance envelopes that contain insulation, reflective roofing systems, airtight construction, and energy-efficient glazing will further enhance thermal performance and reduce operational energy consumption. Studies show that integrated passive design features will reduce the overall energy consumption of a building by 30-60%. Also, advanced low-energy building concepts like Passive House can reduce energy consumption by over 70% based on appropriate climatic conditions[65]. In addition to passive efforts, other advanced technologies, including more efficient Air-Conditioning, Mechanical and Ventilation (ACMV) systems, LED light fixtures, occupancy sensors and energy monitoring systems can provide additional options to reduce the operational energy requirements of buildings. These types of technologies collectively represent a methodology consistent with the efficiency-first concept that most net-zero construction projects are based on. These results also agree with the characteristics of the literature review, which indicates that there is a strong focus on operational energy use reduction in the green building literature[66].

6.2 Renewable Energy Integration and Smart Building Systems

Renewable energy systems support the operational energy usage of buildings once energy demand reduce, leading to net-zero energy use. Solar PV systems are the most prevalent renewable energy systems for buildings because of their declining cost, technological maturity and scalability[67].

Depending on the system capacity and the building's energy requirements, a rooftop PV installation can provide a net metered offset for not more than 75% of maximum demand (MD). Furthermore, the BIPV, by integrating the PV module into the building components, will utilize the available area of the building and also help with the architectural aspects of the building[68].

Using various smart technologies will improve the ability of these energy sources to effectively supply power to businesses and residences as well as allowing individuals to monitor the performance of their own buildings. By utilizing various sensor types (IoT-based sensors), BEMS and other advanced automation platforms, real-time monitoring and optimization of building performance occurs. Research shows that the use of these smart energy management systems has been proven to be able to reduce total energy usage of a building by 15 - 30%, due to the continual performance optimization and control of demand[69].

AI-based predictive control systems (ACS) enhance HVAC performance through dynamic adjustments to operation based on occupancy (people), the anticipated weather pattern, and user behavior. Use of these systems can result in reductions of 10-25% more energy consumed compared to traditional automation systems[70]. The growing significance of energy storage technology close to addressing intermittent renewable energy sources gives rise to the necessity for more energy storage devices, which can store energy produced by renewable energy sources and deliver it to consumers when they require it. At present, lithium-ion battery systems dominate this market and typically provide round-trip efficiencies between 85-95 percent; helping to improve renewable energy use, grid flexibility and energy resilience[71]. Furthermore, the descriptive literature review indicates that the dominant research areas within the green building field are the integration of renewable energy, along with smart building systems. For Sarawak, the combination of abundant hydropower resources, high solar irradiation, and expanding digital infrastructure presents significant opportunities for integrating renewable energy and smart building technologies within future net-zero developments.

6.3 Water Efficiency, Circular Resource Management, and Waste Reduction

Green buildings use every resource more optimally; therefore, they decrease overall resource consumption, not just when it comes to energy, but also with respect to water efficiency and waste generation during the entire lifecycle of a building. Water-efficient technologies will assist in relieving stress on municipal water supplies and in promoting environmental sustainability overall[72].

Low-flow fixtures, dual-flush toilets, rainwater harvesting systems, and greywater recycling are all examples of water conservation measures. Many studies have reported that by implementing these measures, potable water consumption can be reduced by an estimated 30-60% when compared to traditional facilities[73]. In Sarawak, where the annual rainfall is high, rainwater harvesting systems provide an excellent opportunity to reduce the amount of potable water required.

Managing waste is as important to sustainable building development as is the act of constructing buildings. Since constructing and demolishing buildings creates a large amount of solid waste worldwide, it is imperative to apply circular economy principles in constructions and demolitions[74]. Applying the principles of circular economy through material recovery and recycling, using modular construction, and segregating waste from construction compiles to divert at least 60-80% of construction waste from landfills; thereby reducing the amount of virgin materials that need to be used[75]. Implementing circular resource management principles supports environmental performance and optimizes long-term resource use making circular resource management principles essential to sustainable building development strategy development.

6.4 Sustainable Materials and Embodied Carbon Reduction

As the operational energy efficiency of buildings improves, the embodied carbon in the building materials used is becoming increasingly important for lifecycle greenhouse gas emissions. Therefore, sustainable materials selection is critical for meeting net-zero building goals[76]. Conventional building materials (cement and steel) contribute a lot of carbon pollution to the environment. Cement production produces approximately 7–8 percent of the greenhouse gases (GHG) generated worldwide and is one of the largest contributors of industrial emissions globally [77]. One way to reduce material-based emissions by as much as 30–70 percent (without affecting structural performance or integrity) is by replacing conventional Portland cement with supplemental cementitious materials like fly ash or slag, and other industrial waste products[78].

Likewise, using recycled steel reduces both energy consumption and embodied carbon, compared with primary steel production[79]. Other bio-based materials, such as bamboo, engineered timber and hemp-based products, are also additional ways to help people to reduce the environmental effects of their construction projects while also supporting the ability of materials to be used again. An example of this would be Cross-laminated timber (CLT). Studies have shown that CLT reduces the amount of embodied carbon in buildings by about 80%, compared to conventional reinforced concrete buildings[80].

The use of Lifecycle Assessment (LCA) to evaluate environmental impacts related to the extraction of materials, the manufacturing of products, how they are developed, operated, and disposed of is a widely accepted methodology for the systematic evaluation of these impacts. Studies show that being aware of LCA when designing a project can reduce total lifecycle environmental impacts by 20 to 40%, therefore incorporating embodied carbon into projects as an integral part of the overall planning process is critical[81]. Unfortunately, relevant literature finds that there is less empirical evidence available on embodied carbon and emissions from material use than there should be, considering their increasing importance in regard to overall lifecycle emissions.

6.5 Digital Technologies, Performance Monitoring, and Building Optimization

In order for green and net-zero buildings to be built successfully, there needs to be an ongoing evaluation of how well they are performing. This evaluation is a continual process of monitoring the building's performance from day one until the end of the building's useful life, using data to optimise the performance. Sustainable development for a building is an on-going challenge of closing the performance gap, which is created by actual energy use versus predicted design performance.

According to studies, operational energy consumption could be 30 to 50% higher than expected if buildings do not have a good method for recording how well they perform and managing their performance[82]. The new digital technologies adopted by more modern buildings include Building Information Modeling (BIM), Digital Twins, IoT sensors and Building Energy Management Systems (BEMS)[83].

Integrated Design, Simulation & Lifecycle Management - BIM make possible for the project team to assess performance in terms of sustainability prior to construction, while the more sophisticated Digital Twin platforms further develop this capability by providing virtual representations of buildings in real time through continuous acquisition of operational data through various types of sensors and systems that are part of the physical building.

Performance improvement through Post-Occupancy Evaluation (POE) occurs by evaluating the actual operation of the building, the level of satisfaction of those who occupy and use the building and how energy is used after the building is complete. Research indicates that continuous monitoring along with feedback from the occupants can help to increase operation efficiency by 10%-20% over time through adaptive system optimization and through adjustments to the behaviour of individuals[83, 84].

For Sarawak, expanding adoption of BIM, digital monitoring platforms, and smart building analytics offers significant opportunities to improve building performance, strengthen carbon reporting, and support evidence-based decision-making in future net-zero developments.

Table 6: Green and Net-Zero Building Strategies and Reported Environmental Performance Impacts from Reviewed Literature

Strategy Category	Key Technologies	Potential Benefits	References
Passive Design	Orientation, shading, natural ventilation, high-performance envelopes	20–60% energy reduction	[85, 86]
Energy Efficiency	Efficient HVAC, LED lighting, energy management systems	15–40% operational savings	[87, 88]
Renewable Energy	Solar PV, BIPV, battery storage	30–100% electricity offset	[89]
Smart Buildings	IoT, AI controls, BEMS, Digital Twins	15–30% energy optimization	[90]

Strategy Category	Key Technologies	Potential Benefits	References
Water Efficiency	Rainwater harvesting, greywater recycling, low-flow fixtures	30–60% water savings	[91]
Circular Resource Management	Recycling, modular construction, waste recovery	60–80% waste diversion	[74, 92]
Low-Carbon Materials	Fly ash concrete, recycled steel, CLT, bamboo	30–80% embodied carbon reduction	[93]
Lifecycle Assessment	LCA-based design and material optimization	20–40% lifecycle impact reduction	[94]

The key green building strategies along with their relevant Environmental Performance Benefits are shown in Table 6. Energy efficiency, passive design and renewable energy integration are the major strategies believed to reduce operational energy demand. Meanwhile, embodied carbon reductions and circular resource management are recognised more widely but there is still an insufficient body of research to support these findings. As such, there is a clear need for more balance between operational vs embodied carbon reduction strategies in future research.

Achieving net-zero buildings can involve using an inclusive strategy which includes utilizing many sources of low-carbon material; improved energy efficiency; using different kinds of renewable energy systems; and developing a sound set of governance mechanisms. Net-zero readiness is defined in the context of both new and existing buildings as the ability for them to have net-zero operational and embodied carbon emissions through coordinated design, construction, operation, and retrofitting strategies [18, 95]. In order to achieve net-zero goals, regions such as Sarawak, will require balancing the technological innovations that will help them achieve those goals against the economic feasibility, institutional capacity and stakeholder collaboration that they may require to achieve those goals.

The main focus is to reduce the carbon footprint of the lifecycle, using LCA methods and low carbon materials. Recent studies show that the embodied carbon of high-performance buildings can be as high as 40-70% of the total lifecycle emissions, highlighting the need to consider more than just operational energy efficiency[96, 97]. The use of alternative materials to reduce the use of resources, the use of circular construction methods, and the ability to design buildings for adaptability are all methods for significantly reducing the environmental impacts of construction and promoting sustainable long-term.

Another crucial method to achieve net-zero buildings is through retrofitting of our existing buildings, as it is expected that most of the building stock available in 2050 already exists today. By performing deep energy retrofits that include improvements to the building envelope, the use of energy efficient HVAC systems, the use of smart controls, and various electrification technologies, you can achieve a at least a 50–80% reduction in your energy consumption and a significant reduction in your operational carbon emissions [98]. This is especially true in Sarawak where many of the public and commercial buildings can benefit from upgrades to their performance and energy efficiency.

In addition to supporting net-zero transitions, the integration of renewable energy supports the transition to net-zero transitions, by providing renewable energy systems (solar photovoltaic systems, building-integrated photovoltaics, and energy storage technologies) to help reduce power consumption from the grid and improve energy resilience and reduce reliance on fossil fuel-based electricity generation[18, 99]. The abundance of hydroelectricity in Sarawak and the increasing potential for solar-generated power make it possible for the development of low-carbon buildings using renewable energy resources.

In order to successfully achieve net-zero, a focus on efficiency, combined with the implementation of renewable energy sources and the use of circular construction methods, is essential. This will require the establishment of regulatory frameworks that support Malaysia's transition to net-zero, investments in green technologies, improved stakeholder capabilities, and ongoing measurement of performance levels[100]. The net zero building pathway provides substantial opportunities for Sarawak to use its renewable energy resources as well as overcome the significant barriers currently facing

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the development of net zero buildings (financing, technical expertise, and implementation capacity) through collaboration between all stakeholders (government, industry, and academia). The built environment can thus contribute to supporting national decarbonization and sustainable development efforts[101].

6.6. Conceptual Model Summary

According to the synthesized literature review, the development of green buildings in Sarawak can be viewed as a socio-technical transition process influenced by four dimensions: (1) policy (regulatory/governance), (2) technology (enabling/performing), (3) finance (making it economically feasible), and (4) stakeholders (implementing through coordination). These four dimensions collectively affect the degree to which green buildings have been adopted, the degree to which buildings are energy-efficient, the degree to which carbon footprint has been reduced, and the overall transition to net-zero buildings. The framework may be used as an analytical tool to examine structural elements, technical elements, and behaviors that impact the development of a sustainable built environment in Sarawak. This conceptualization correlates with the results of the quantitative descriptive analysis which illustrates the interdependence between the four technological, policy, financial, and stakeholder dimensions that shape sustainable transitions. The detail has been presented in Figure 3.

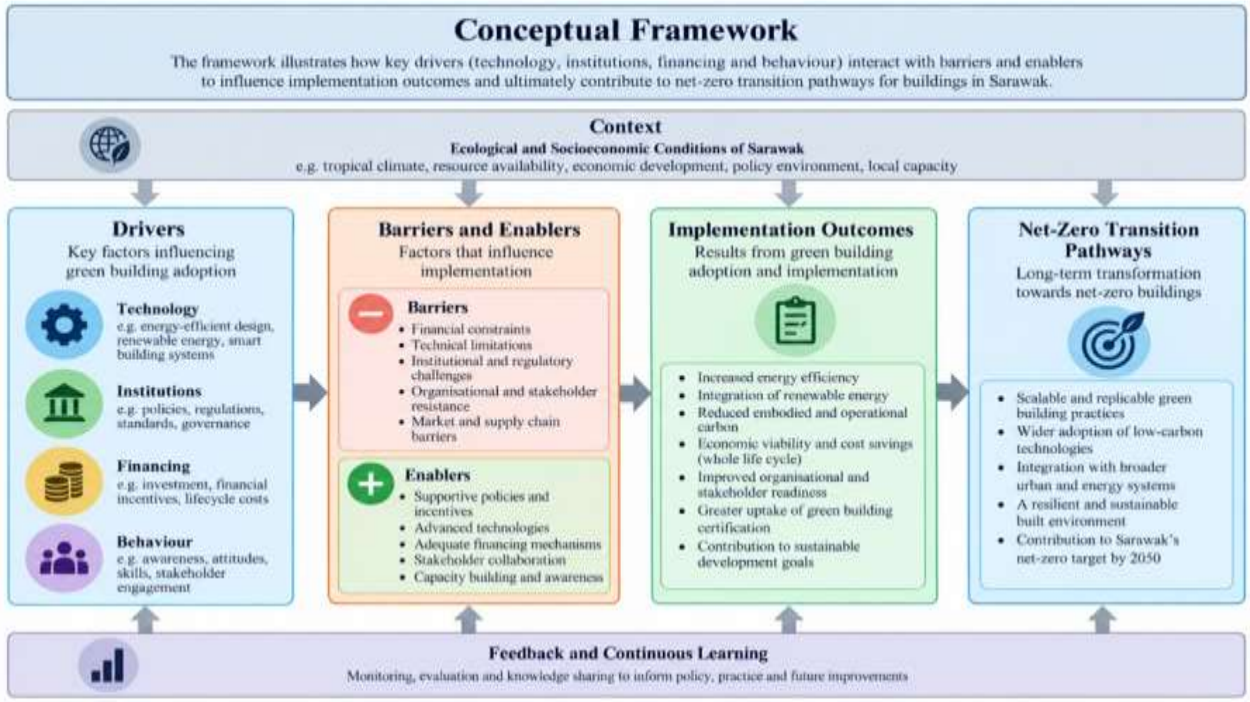

Figure 3. Conceptual Framework of Drivers, Barriers, Enablers, Implementation Outcomes and Net-Zero Transition Pathways for Green Buildings in Sarawak.

7. DISCUSSION

7.1 Synthesis of Key Findings

This review draws on evidence from global, Malaysian and Sarawak literature to build a cohesive understanding of the transition to green and net-zero buildings in tropical developing countries. In the Malaysian context, this transition is further supported by a progressive policy landscape such as the National Green Technology Policy (NGTP) 2009 [108] and the Green Technology Master Plan (GTMP) 2017–2030 [109], which sees green technology and energy efficiency as a core element of sustainable development. In addition, the National Climate Change Policy 2009 [112] views the building sector as part of wider climate change and decarbonization efforts, and the National Energy Efficiency Policy and Action Plan (NEAAP) 2.0 (2026–2035) [113] strengthens the policy focus on energy efficiency, including in buildings. The initiatives led by the Sustainable Energy Development Authority Malaysia (SEDA) provide an additional policy and institutional context for renewable energy integration and decarbonization for the net-zero transition. Against this policy background, the literature reviewed, supported by a descriptive quantitative analysis of the included studies, demonstrates that energy efficiency, policy frameworks and technological strategies are the dominant research areas, but also emphasizes the importance of understanding how these policy ambitions are translated into practice at building and project level.

In summary, research suggests green building is now more limited by integration throughout systems than by being technically feasible, with constraints associated with the various systems (policy, technology, finance, and various stakeholders). Even though the use of technologies that facilitate passive design, renewable energy, smart technologies, and low carbon materials has been widely accepted, their success is dependent upon the presence of an enabling institutional and financial environment.

Malaysia has developed a composite of federal-level policy instruments, technical standards, rating tools, and strategic roadmaps to develop a policy and regulatory framework for green and energy-efficient buildings. These include MS 1525 [107], Green Building Index (GBI), National Green Technology Policy (NGTP) 2009 [108], Green Technology Master Plan Malaysia 2017-2030 [109], National Climate Change Policy 2009 [112], National Energy Policy 2022-2040 [110], and National Energy Transition Roadmap (NETR) [111] [1–7] Together, these instruments provide the broader national policy and technical context for energy efficiency, green buildings, decarbonization, and the transition towards a low-carbon energy system. MS 1525 provides technical guidance on energy efficiency and renewable energy use in non-residential buildings, while the GTMP specifically identifies buildings as one of its key sectors for green technology development. [1,4] The NETR also provides a national roadmap for Malaysia's energy transition and low-carbon development. [7] The National Energy Efficiency Policy and Action Plan (NEEAP) 2.0 (2026-2035) has recently enhanced the national focus on energy efficiency and conservation in the industrial, commercial, and domestic sectors. [113] [8]

However, the federal policy and strategic framework must be distinguished from the legal and regulatory arrangements operating in Sarawak. Federal policies and strategic instruments provide an important national context, but their legal applicability and mechanisms for implementation may differ by jurisdiction. The difference is especially important for energy efficiency. The Energy Efficiency and Conservation Act 2024 (Act 861), which came into force on 1 January 2025, provides a federal legislative framework for energy efficiency and conservation. However, the Act is not applicable to Sabah and Sarawak. [114, 115] [9, 10] Therefore, the Act should not be regarded as the legal framework governing energy efficiency in Sarawak. Energy and electricity matters in Sarawak are dealt with under the state's own institutional and legal framework. The Ministry of Energy and Environmental Sustainability Sarawak (MEESty) is responsible for energy and environmental sustainability policy and related matters at the state level. [117] [11] Sarawak has also developed its own energy-transition policy framework through the Sarawak Energy Transition Policy (SET-P), launched in 2025. [12] In this regard, Sarawak presents a unique regulatory environment in which national policy objectives on energy efficiency, green buildings, and decarbonization are embedded in state-specific institutional arrangements, legislation, and implementation mechanisms. [116]

Generally technological point, studies show that the total energy and carbon reductions that can be achieved via integrated design solutions will vary from 20%-60%, but they can all be achieved; however, green building performance actually achieves less of what was predicted by design due to issues related to the way buildings have been operated during their lifetime, how tenants operate building systems, and lack of suitable monitoring systems.

Lifecycle cost analysis and green financing mechanisms validate and support that sustainable construction is a viable long-term investment. Nevertheless, high initial costs and perceived risk are two major factors deterring the acceptance of sustainable building practices by private developers in developing nations.

The stakeholder analysis confirmed the strong interdependencies of various parties involved in developing green buildings such as government organizations, developers, engineers, utility companies, and banks. Weak cooperation and fragmentation of roles are important impediments to increasing the use of net-zero built environments. This relationship between stakeholders is consistent with the theme distribution of the research literature analyzed (overwhelmingly policy&technology driven studies versus those focused on stakeholders&implementation).

7.2 Contradictions and Tensions in Literature

Despite broad consensus on the benefits of green and net-zero buildings, several contradictions emerge across the literature.

First, there is a clear tension between short-term economic perceptions and long-term lifecycle benefits. While multiple studies demonstrate lifecycle cost savings of 20–30% for green buildings, developers in developing contexts such as Malaysia continue to prioritize initial capital costs over long-term operational savings. This indicates a behavioral and market perception gap rather than a technical limitation.

The second contradiction is that simulated designs show tremendous energy savings; however, real-world data indicate that buildings consume more energy than predicted. This shows the shortcomings of existing design tools and the effect of factors that affect a building's operation after occupancy. Empirical studies have indicated a performance gap in a level of energy use above 30-50% of predicted, or greater, energy consumption.

Third, there is a potential gap between the degree of ambition in federal and state decarbonization policies and their implementation. At the federal level Malaysia has implemented strategic instruments such as the National Energy Policy 2022–2040, NETR and NEEAP 2.0. However, the legal and regulatory status of these instruments differs across jurisdictions. In particular, it should not be assumed that federal energy legislation will be directly applicable to Sarawak. In Sarawak, implementation has to be understood within the state's own institutional and legal framework. MEESty has the mandate of energy and environmental sustainability policy, while Sarawak-specific legislation and regulatory arrangements support electricity governance. The transition to net-zero buildings in Sarawak is therefore a synthesis of alignment with the national decarbonization agenda and implementation through the state's jurisdictional scope.

Fourth, even if renewable energy resources like photovoltaic (PV) technology and intelligence systems are well promoted, their integration into the constructed environment is still inconsistent because of infrastructure limitations, difficulty obtaining financing, and insufficient technical expertise.

These inconsistencies show that the issue is not a lack of solutions; it's the lack of systemic alignment among governance, finance and implementation structures. In the Sarawak context, this systemic alignment also requires coordination between Federal strategic objectives and State-level energy institutions, legislation, and implementation mechanisms. This contradiction is also reflected in the literature analysis; there are more studies on technological performance than on implementation or behavioral issues.

7.3 Research Gaps Identified

The synthesis of existing literature points to numerous important gaps in research that support the contribution of this study. These gaps are reflected, in part, in the limited degree to which the literature we reviewed presented themes focused on stakeholders or on the implementation of net-zero technology in the quantitative description of the literature we analysed.

First, there are two major areas where research appears to be absent from existing literature. The first significant gap is the absence of integrated socio-technical frameworks that connect together policies, technology, finance, and stakeholders as one cohesive model. Most of the studies that we reviewed are primarily concerned with each of these elements separately, which creates fragmented knowledge surrounding net-zero technology transition.

The inconsistencies demonstrate that the problem is not a lack of solutions but a lack of systemic alignment between governance, finance and implementation structures. In the Sarawak context, this systemic coordination also involves the synchronization of federal strategic objectives and state level energy institutions, legislation and implementation mechanisms. The literature analysis also reveals this contradiction, as it shows more studies on technological performance compared to those on implementation or behavioral issues.

Second, little research examines implementation contexts at the sub-national level, and particularly in developing tropical economies such as Sarawak. Research on Malaysia in general has received moderate attention, but issues concerning the specific energy context of Sarawak (a context characterized by a heavy reliance on hydropower, rapid urbanization, and a distinctive form of state-level autonomy in energy production and consumption) have received little academic attention. This gap is crucial, especially since Sarawak has its own institutional and legal framework for energy and electricity governance. Consequently, federal energy policies and roadmaps cannot be assumed to have identical implementation mechanisms or regulatory effects in Sarawak.

More research is needed specifically on the interaction of federal strategic instruments such as the National Energy Policy 2022–2040, NETR and NEEAP 2.0 with Sarawak's own energy policies, institutions, ordinances and regulatory arrangements. This would help clarify how national decarbonization objectives can be aligned with Sarawak's unique jurisdiction and development priorities.

Third, there is a need for additional empirical research evaluating the difference between certified green buildings and their actual operational performance, particularly in locations with warm temperatures and large cooling loads.

Fourth, past studies focus either on the technology required to meet the vision for how much energy to use or the policies that need to be created to support the use of that technology, while fewer studies focus on how institutions will organize themselves for effective stakeholder coordination to enable green building use in real life.

Finally, there is a need for more transition-oriented research that identifies paths toward achieving net-zero targets at the regional level in a manner that supports state decarbonization goals by 2050.

7.4 Implications of the Findings

According to the results of the study, it is likely that achieving net-zero buildings in Sarawak will necessitate a transition to an integrated systems approach rather than isolated interventions. The effectiveness of policy instruments will require not just strengthening enforcement mechanisms but also creating a system that aligns private sector incentives for using net-zero-related systems. In Sarawak, such mechanisms should be developed with consideration of the state's own energy governance and regulatory jurisdiction, while remaining aligned with relevant federal energy-transition objectives. In addition to building policies and having enforcement mechanisms, the financial system needs to better assist long-term investment decisions through the use of green finance instruments and lifecycle-based evaluations.

Complementing technological adoption with improved performance measurement systems will be critical to achieving net-zero buildings. These include improved post-occupancy evaluation processes and real-time energy management systems. At the same time, there will need to be an institutionalized approach to coordinating stakeholders through collaborative project delivery models and capacity-building activities. In this context, coordination between federal and Sarawak institutions is particularly important. Federal strategies may provide broader national direction on energy transition, energy efficiency, and decarbonization, while Sarawak-specific institutions and legislation determine the relevant mechanisms for energy and electricity governance within the state. MEESty therefore represents an important institutional reference for discussions concerning energy and environmental sustainability in Sarawak, rather than treating federal energy regulatory bodies as directly responsible for the state's electricity governance.

Overall, transitioning to net zero buildings represents much more of a governance and systems integration challenge than a technological one and will require coordinated action in multiple sectors. The implications of this research match closely with the distribution patterns of the thematic data identified in the descriptive analysis, indicating that equal consideration of factors related to policy, technology, and finance, along with all stakeholder groups, will be necessary in achieving this goal. For Sarawak, this transition should be understood within the state's distinct energy jurisdiction while recognizing the relevance of broader federal policy directions and national decarbonization objectives.

8. CONCLUSIONS

Through this study, an overview and synthesis of the existing knowledge pertaining to green and net zero building development was conducted with particular reference to Sarawak, Malaysia, but in relation to the global climate change agenda established with decarbonization and a target date of 2050 for net zero. Evidence for this study was obtained from peer-reviewed journals, international reports, and policy documents to provide a systematic understanding of how policy frameworks, technological systems, financial instruments (mechanisms), and, in particular, stakeholder dynamics influence and dictate progress toward sustainable low-carbon buildings. Through quantitative analysis of all studies reviewed, there appears to be a strong research trend for green building development across each of the four areas of focus (policy, technology, finance, and stakeholders).

This implies that green building development is no longer limited due to technology (many passive designs have been successfully used, and renewable energy systems can be integrated into new buildings). In fact, there is currently a large supply of viable new technologies that will assist green building development (smart building technologies, lifecycle carbon assessment methods, and low-carbon construction materials). As a result, the greatest challenge for building projects today and going forward will be how to meaningfully integrate the solutions available into the systems that are applied within projects and ensure their consistent application across all projects. The policies that promote sustainability in Malaysia include the following policies: MS 1525, GBI, and NETR. Assessment frameworks comprise MyCREST and GreenRE, which also support them. There are internationally recognized rating systems like LEED, BREEAM, and EDGE.

However, the voluntary nature of many international green building requirements, along with inconsistent enforcement methods, reduces their effectiveness in facilitating transformative change on a large scale. In Sarawak, while the advantage at the state level of having significant resources available for hydro-generated electricity and other renewable energy sources provides the states with strong supporting conditions for sustainable development, the implementation of these initiatives has been limited thus far due to limited technical expertise, slow progress in developing markets, and poor performance tracking. From a technology perspective, the research supports the possibility of generating substantial energy use and carbon emissions savings with integrated building design strategies. Nonetheless, there continues to be a gap in performance between anticipated and actual energy use, which demonstrates why it is so important to continue performing post-occupancy evaluations (POEs), deploying real-time monitoring systems, and utilizing effective operational management. The study demonstrates that simply deploying technology does not guarantee results and must be engaged with ongoing feedback to optimize systems continuously.

The long-term financial benefits of producing green buildings through lifecycle costing and green finance mechanisms show that these buildings can save on operating expenses and improve the value of the property. However, the adoption is still hampered by the high upfront capital investment costs and perceived investment risks associated with green buildings (particularly in emerging or developing markets). In light of these challenges, there is a greater need for innovative financial tools (such as stronger financial instruments) to create more incentives and establish market-based strategies that support sustainable investment decisions.

The success of transforming buildings into net-zero buildings is highly reliant on collaboration and coordination between stakeholders, which include, but are not limited to, all levels of government, developers, contractors, property consultants, utilities, financial institutions, and end-users. Through effective collaboration and currently fragmented responsibilities among those stakeholders, limited capacity-building efforts will continue to be a major barrier to the effective implementation of net-zero buildings in Sarawak and like contexts.

This study determines that the transition to net zero buildings is not simply a technical issue but rather one of social and technical transformation. Net zero buildings can be achieved through alignment of policy direction, technological innovation, funding viability, and all stakeholders working together for a sustained and meaningful effect.In conclusion, achieving net-zero buildings in Sarawak by the year 2050 is technically feasible, but it is highly complicated from an institutional and financial perspective. The success of net zero buildings in Sarawak will come from coordination actions across multiple levels to align the level of policy aspiration with the level of technical capability; the financial supports needed to provide net zero buildings; and the collaboration required by all stakeholders.

Research Contribution

The purpose of this research is to integrate Policy-Tech-Finance-Stakeholder themes within the Sarawak region through the creation of a developed conceptual model. This study will also consolidate fragmented literature into a coherent narrative highlighting obstacles and obstacles to achieving net-zero building development within tropical developing regions. The constraints identified in this model and above are based on a combination of qualitative thematic analysis and descriptive quantitative patterns extracted from the body of research analyzed above.

Practical Implications

The implications of this research are significant for policy-makers, industry practitioners and urban planners. Policymakers should put in place stronger enforcement mechanisms, as well as establish greater mandatory sustainability requirements for all regulated entities. For those in the industry, integrated design approaches, and development of digital performance monitoring systems should be a priority. Financial institutions should create more green financing options that will reduce upfront costs and make it more attractive to invest in these types of projects.

9. FUTURE RESEARCH PRIORITIES AND POLICY IMPLICATIONS

Despite there are many new developments being made in the area of research and practice for green building, there are still many obstacles that will inhibit the transition to low-carbon and net-zero environments. One large gap in research is how little innovation has been made in the area of integrating the assessment of embodied carbon into the primary building design and decision-making processes. Although the energy required to operate buildings has received a great deal of emphasis, the amount of embodied carbon may comprise 40–70% of the total life cycle emissions of high-performance structures; therefore, there is a pressing need for increased adoption of lifecycle assessment (LCA) methods for project planning and selection of materials[78, 102].

The other major challenge to address is the continued gap between predicted and actual performance of buildings. Building users' individual behaviours and methods of operation as well as the management of their systems may cause energy usage to exceed what was originally designed for in all cases; therefore, research in the future needs to concentrate on actual evaluation after occupation, real-time monitoring, and performance management driven by collected data so as to produce better long-term building processes[82].

Future initiatives for Sarawak should focus on developing localized green building implementation frameworks that are specific to the state's climate conditions, renewable energy potential and socio-economic situation. While there are national certification schemes such as GBI, GreenRE and MyCREST that provide useful guidance, only a handful of studies has been conducted on adapting these frameworks to the unique development environment of Sarawak. Future work should explore region-based sustainability criteria and implementation mechanisms for large-scale adoption[103, 104].

Digital technologies also have significant potential to aid the development of sustainable buildings. For example, Building Information Modeling, the Internet of Things, Artificial Intelligence and digital twin technologies are all able to create methods for improving energy consumption, monitoring performance, and managing the lifecycle of buildings. Each of these technologies has been shown to significantly reduce energy use during operations and will allow for data-driven decision-making at all stages of a building's lifecycle[69, 83, 88].

It will also provide an additional platform for more businesses to join through stronger policy support in form of regulations, financial incentives and green purchase. Capacity building programs, professional development training programs and collaboration between industry and educational institutions will improve the development of technical skills and innovative products in the building sector. Lastly, more emphasis on the development of local supply chains for low carbon materials and renewable energy technologies will help bring down the cost of implementation and improve access to market[105, 106].

To achieve net-zero and climate-resilient buildings, future actions must be coherent across all areas of public policy, industry, technology and research. In Sarawak, the use of renewable energy resources, the expansion of opportunities for capacity building and the promotion of integrated sustainability practices will provide viable pathways for Low Carbon Development. Furthermore, ongoing research, innovation and stakeholder cooperation will be necessary to support Malaysia's overall agenda for decarbonisation, and achieve long-term sustainability goals.

REFERENCES

[1] A. Anisie, J. P. J. Navarro, T. Antic, F. Pasimeni, and H. Blanco, "Innovation landscape for smart electrification: Decarbonising end-use sectors with renewable power," 2023.

[2] D. Kaya and F. Ç. Kılıç, "Renewable energies, clean energy generation and their subsidies in Turkey and Eu countries," *Jestech,* vol. 15, pp. 113-122, 2012.

[3] I. Hamilton, H. Kennard, O. Rapf, J. Amorocho, S. Steuwer, J. Kockat*, et al.*, "Global Status Report for Buildings and Construction-Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector," 2024.

[4] Y. Liang, C. Li, Z. Liu, X. Wang, F. Zeng, X. Yuan*, et al.*, "Decarbonization potentials of the embodied energy use and operational process in buildings: A review from the life-cycle perspective," *Heliyon,* vol. 9, 2023.

[5] S. R. Aldhshan, K. N. Abdul Maulud, W. S. Wan Mohd Jaafar, O. A. Karim, and B. Pradhan, "Energy consumption and spatial assessment of renewable energy penetration and building energy efficiency in Malaysia: A review," *Sustainability,* vol. 13, p. 9244, 2021.

[6] J. Taherahmadi, Y. Noorollahi, and M. Panahi, "Toward comprehensive zero energy building definitions: a literature review and recommendations," *International Journal of Sustainable Energy,* vol. 40, pp. 120-148, 2021.

[7] X. Y. Tan, N. Mahyuddin, and S. M. Zaid, "A NARRATIVE REVIEW TO ACHIEVE NET-ZERO ENERGY HOMES IN MALAYSIA," *Journal of Surveying, Construction and Property,* vol. 16, pp. 133-149, 2025.

[8] R. E. Amaral, J. Brito, M. Buckman, E. Drake, E. Ilatova, P. Rice*, et al.*, "Waste management and operational energy for sustainable buildings: a review," *Sustainability,* vol. 12, p. 5337, 2020.

[9] A. Hassan, S. M. Asharuddin, and M. F. Sukaimy, "Constraints in Implementation of Green Building Projects in Malaysia: A Short Review," *Emerging Advances in Integrated Technology,* vol. 4, pp. 27-32, 2023.

[10] O. Marzouk, "Summary of the 2023 report of TCEP (tracking clean energy progress) by the International Energy Agency (IEA), and proposed process for computing a single aggregate rating," *Available at SSRN 5099325,* 2025.

[11] I. Farouk, Y. I. Go, and M. Fernandez, "Evaluation of energy scenarios for Malaysia for energy transition in meeting net-zero target 2050," *Next Energy,* vol. 7, p. 100295, 2025.

[12] E. Z. Bower, M. Hiebert, D. L. Pumphrey, G. B. Poling, and M. A. Walton, *Sustainable Energy Futures in Southeast Asia*: Center for Strategic and International Studies (CSIS), 2012.

[13] K. Sopian, M. H. Hakemzadeh, and H. A. Kazem, "the Tropical Climate Conditions," *Reducing the Effects of Climate Change Using Building-Integrated and Building-Applied Photovoltaics in the Power Supply,* p. 163, 2024.

[14] R. H. Abdellah and M. A. N. Masrom, "Exploring the barriers of net zero energy buildings (NZEBS) implementation in Malaysia: perception of Malaysian construction practitioners," *International Journal of Integrated Engineering,* vol. 10, 2018.

[15] N. A. B. Mohd Taharill and M. F. Ayob, "A methodology to investigate financial challenges and strategic responses of Net Zero Building in Malaysia," *The International Competition on Sustainable Education 2025 E-Proceeding,* pp. 511-513, 2025.

[16] A. Gugliandolo, L. La Notte, A. L. Palma, and B. Di Pietra, "The Smart Readiness Indicator as a Conceptual Framework for Sustainable Building Decarbonisation and Digitalisation Governance," *Sustainability,* vol. 18, p. 1532, 2026.

[17] J. Wachsmuth, P. Warnke, A. Gambhir, S. Giarola, K. Koasidis, S. Mittal*, et al.*, "Co-creating socio-technical scenarios for net-zero emission pathways: Comparison of five national case studies," *Renewable and Sustainable Energy Transition,* vol. 4, p. 100064, 2023.

[18] A. J. Marszal, P. Heiselberg, J. S. Bourrelle, E. Musall, K. Voss, I. Sartori*, et al.*, "Zero Energy Building–A review of definitions and calculation methodologies," *Energy and buildings,* vol. 43, pp. 971-979, 2011.

[19] I. Sartori, A. Napolitano, A. J. Marszal, S. Pless, P. Torcellini, and K. Voss, "Criteria for definition of net zero energy buildings," in *Proceedings of EuroSun*, 2010.

[20] B. N. Porfiriev, A. Dmitriev, I. Vladimirova, and A. Tsygankova, "Sustainable development planning and green construction for building resilient cities: Russian experiences within the international context," *Environmental Hazards,* vol. 16, pp. 165-179, 2017.

[21] S. Pandey, "Impact of green building rating systems on the sustainability and efficacy of green buildings: case analysis of green building index, malaysia," *Malaysia.[(accessed on 24 August 2019)],* 2018.

[22] Y. Elaouzy and A. El Fadar, "Energy, economic and environmental benefits of integrating passive design strategies into buildings: A review," *Renewable and sustainable energy reviews,* vol. 167, p. 112828, 2022.

[23] I. A. Gondal, M. Syed Athar, and M. Khurram, "Role of passive design and alternative energy in building energy optimization," *Indoor and Built Environment,* vol. 30, pp. 278-289, 2021.

[24] C. J. Kibert, *Sustainable construction: green building design and delivery*: John Wiley&Sons, 2016.

[25] L. Chen, L. Huang, J. Hua, Z. Chen, L. Wei, A. I. Osman*, et al.*, "Green construction for low-carbon cities: a review," *Environmental chemistry letters,* vol. 21, pp. 1627-1657, 2023.

[26] V. Anand, V. L. Kadiri, and C. Putcha, "Passive buildings: a state-of-the-art review," *Journal of infrastructure preservation and resilience,* vol. 4, p. 3, 2023.

[27] A. Adnan, S. B. Abd Karim, and M. H. Mustafa, "Integrating Sustainable Building Design Criteria to the Green Building Index (GBI) and MyCREST in Malaysia: Insights from a Systematic Review and Meta-Analysis," *Journal of Design and Built Environment,* pp. 58-84, 2025.

[28] M. Z. A. Hassan, A. N. Harun, and M. N. M. Nawi, "ENVIRONMENTAL SUSTAINABILITY PERFORMANCE ASSESSMENT FRAMEWORK–CRITICAL REVIEW OF GREEN BUILDING RATING TOOLS," *MALAYSIAN CONSTRUCTION RESEARCH JOURNAL (MCRJ),* p. 185.

[29] S. A. M. Ghazali, N. S. M. Zaid, and N. H. Ishak, "Implementing Energy Efficiency Standard in Buildings: Occupants Awareness and Challenges," *International Journal of Real Estate Studies,* vol. 16, pp. 16-23, 2022.

[30] A. Alaraj and M. Szabó, "Sustainable Transformation of the Construction Industry in Developing Countries: Evidence from Jordan, Malaysia, and Türkiye," *Periodica Polytechnica Social and Management Sciences,* 2026.

[31] A. Darko and A. P. C. Chan, "Strategies to promote green building technologies adoption in developing countries: The case of Ghana," *Building and Environment,* vol. 130, pp. 74-84, 2018.

[32] L. C. Lau, E. Ajien, I. T. Hanafi, M. Y. M. Lee, Z. Januri, G. S. C. Chan*, et al.*, "Potential of biogas utilization for renewable energy mix contribution and rural electrification in Sarawak," *Reviews in Agricultural Science,* vol. 11, pp. 54-75, 2023.

[33] A. M. Alawag, F. K. Alqahtani, W. S. Alaloul, M. Liew, A. O. Baarimah, A.-B. A. Al-Mekhlafi*, et al.*, "Developing framework for implementing total quality management (TQM) in sustainable industrialized building system (IBS) in construction projects," *Sustainability,* vol. 16, p. 10399, 2024.

[34] A. M. Y. Ting, S. Y. Wong, P. A. Palis, and E. A. Ellie, "CONTRACTORS'PERSPECTIVE ON THE MATURITY LEVEL OF GREEN BUILDING PRACTICES IN THE SARAWAK CONSTRUCTION INDUSTRY," *Journal of Surveying, Construction and Property,* vol. 16, pp. 1-10, 2025.

[35] Z. Zakaria, N. R. M. Ariff, N. M. A. Noorhani, and M. M. Hussain, "Sustainable Green Building Initiatives in Malaysia: Issues In The Implementation Practices," *Planning Malaysia,* vol. 22, 2024.

[36] M. Shan and B.-g. Hwang, "Green building rating systems: Global reviews of practices and research efforts," *Sustainable cities and society,* vol. 39, pp. 172-180, 2018.

[37] I. Gudac Hodanić, H. Krstić, I. Marović, and M. Gudac Cvelic, "The Role of the Built Environment in Achieving Sustainable Development: A Life Cycle Cost Perspective," *Sustainability,* vol. 17, p. 8996, 2025.

[38] C. Langston, *Life-cost approach to building evaluation*: Routledge, 2013.

[39] G. H. Berghorn, *Life cycle cost-based risk model for energy performance contracting retrofits*: Michigan State University, 2014.

[40] I. Citaristi, "International Finance Corporation—IFC," in *The Europa Directory of International Organizations 2022*, ed: Routledge, 2022, pp. 333-335.

[41] J. Zuo and Z.-Y. Zhao, "Green building research–current status and future agenda: A review," *Renewable and sustainable energy reviews,* vol. 30, pp. 271-281, 2014.

[42] Y. Yong Lee, M. Syaznie Ikqmal Azmi, and Y. Huei Lee, "A study on the challenges of implementing green building concept in Sarawak, Malaysia," in *IOP Conference Series: Materials Science and Engineering*, 2020, p. 012022.

[43] K. Y. Mok, G. Q. Shen, and R. Yang, "Stakeholder complexity in large scale green building projects: A holistic analysis towards a better understanding," *Engineering, Construction and Architectural Management,* vol. 25, pp. 1454-1474, 2018.

[44] M. Temel, R. Lozano, and M. Barreiro-Gen, "Analysing the governance factors for sustainability in organisations and their inter-relations," *Frontiers in Sustainability,* vol. 2, p. 684585, 2021.

[45] R. Lozano and I. Garcia, "Scrutinizing sustainability change and its institutionalization in organizations," *Frontiers in Sustainability,* vol. 1, p. 1, 2020.

[46] A. Al-Otaibi, "Barriers and enablers for green concrete adoption: a scientometric aided literature review approach," *Sustainability,* vol. 16, p. 5093, 2024.

[47] E. C. Hui, Z. Dong, and S. Jia, "How do housing price and sentiment affect consumption distribution in China?," *Habitat International,* vol. 77, pp. 99-109, 2018.

[48] L. B. Robichaud and V. S. Anantatmula, "Greening project management practices for sustainable construction," *Journal of management in engineering,* vol. 27, pp. 48-57, 2011.

[49] M. A. E. Tuah, P. A. Tedong, and M. M. Dali, "The challenges in rural infrastructure planning governance in Sarawak," *Planning Malaysia,* vol. 20, 2022.

[50] O. Ametepey, C. Aigbavboa, and K. Ansah, "Barriers to successful implementation of sustainable construction in the Ghanaian construction industry," *Procedia Manufacturing,* vol. 3, pp. 1682-1689, 2015.

[51] N. Wong and S. Li, "A study of the effectiveness of passive climate control in naturally ventilated residential buildings in Singapore," *Building and environment,* vol. 42, pp. 1395-1405, 2007.

[52] K. A. Babatunde, M. A. Mahmoud, N. Ibrahim, and F. F. Said, "Malaysia's electricity decarbonisation pathways: Exploring the role of renewable energy policies using agent-based modelling," *Energies,* vol. 16, p. 1720, 2023.

[53] Q. K. Qian, E. H. Chan, and A. G. Khalid, "Challenges in delivering green building projects: unearthing the transaction costs (TCs)," *Sustainability,* vol. 7, pp. 3615-3636, 2015.

[54] M. Wang, C. C. Wang, S. Sepasgozar, and S. Zlatanova, "A systematic review of digital technology adoption in off-site construction: Current status and future direction towards industry 4.0," *Buildings,* vol. 10, p. 204, 2020.

[55] D. O. Aghimien, C. O. Aigbavboa, and W. D. Thwala, "Microscoping the challenges of sustainable construction in developing countries," *Journal of Engineering, Design and Technology,* vol. 17, pp. 1110-1128, 2019.

[56] F. V. Mushi, H. Nguluma, and J. Kihila, "A critical review of African green building research," *Building Research & Information,* vol. 50, pp. 610-627, 2022.

[57] A. Darko and A. P. Chan, "Review of barriers to green building adoption," *Sustainable development,* vol. 25, pp. 167-179, 2017.

[58] B. G. Hwang and J. S. Tan, "Green building project management: obstacles and solutions for sustainable development," *Sustainable development,* vol. 20, pp. 335-349, 2012.

[59] C. Liu, C. R. Ahn, X. An, and S. Lee, "Life-cycle assessment of concrete dam construction: comparison of environmental impact of rock-filled and conventional concrete," *Journal of Construction Engineering and Management,* vol. 139, p. A4013009, 2013.

[60] S. D. Djokoto, J. Dadzie, and E. Ohemeng-Ababio, "Barriers to sustainable construction in the Ghanaian construction industry: consultants perspectives," *Journal of Sustainable Development,* vol. 7, p. 134, 2014.

[61] N. Z. Abidin, "Investigating the awareness and application of sustainable construction concept by Malaysian developers," *Habitat international,* vol. 34, pp. 421-426, 2010.

[62] A. Arabkoohsar, A. Behzadi, and N. Nord, "A highly innovative yet cost-effective multi-generation energy system for net-zero energy buildings," *Energy Conversion and Management,* vol. 237, p. 114120, 2021.

[63] A. GhaffarianHoseini, N. D. Dahlan, U. Berardi, A. GhaffarianHoseini, and N. Makaremi, "The essence of future smart houses: From embedding ICT to adapting to sustainability principles," *Renewable and Sustainable Energy Reviews,* vol. 24, pp. 593-607, 2013.

[64] S. Attia, *Net Zero Energy Buildings (NZEB): Concepts, Frameworks, and Roadmap for Project Analysis and Implementation*: Butterworth-Heinemann, 2025.

[65] H. S. Ibrahim, A. Z. Khan, Y. Serag, and S. Attia, "Towards nearly-zero energy in heritage residential buildings retrofitting in hot, dry climates," *Sustainability,* vol. 13, p. 13934, 2021.

[66] M. Santamouris, R. Paolini, S. Haddad, A. Synnefa, S. Garshasbi, G. Hatvani-Kovacs*, et al.*, "Heat mitigation technologies can improve sustainability in cities. An holistic experimental and numerical impact assessment of urban overheating and related heat mitigation strategies on energy consumption, indoor comfort, vulnerability and heat-related mortality and morbidity in cities," *Energy and Buildings,* vol. 217, p. 110002, 2020.

[67] O. F. Orikpete, S. Ikemba, and D. R. E. Ewim, "Integration of renewable energy technologies in smart building design for enhanced energy efficiency and self-sufficiency," *The Journal of Engineering and Exact Sciences,* vol. 9, pp. 16423-01e, 2023.

[68] N. Y. Jadhav, "Renewable Energy Integration in Buildings," in *Green and Smart Buildings: Advanced Technology Options*, ed: Springer, 2016, pp. 109-122.

[69] S. D'Oca, T. Hong, and J. Langevin, "The human dimensions of energy use in buildings: A review," *Renewable and Sustainable Energy Reviews,* vol. 81, pp. 731-742, 2018.

[70] A. Afram and F. Janabi-Sharifi, "Theory and applications of HVAC control systems–A review of model predictive control (MPC)," *Building and environment,* vol. 72, pp. 343-355, 2014.

[71] G. Energy, "Net Zero by 2050," *International Energy Agency, June,* 2021.

[72] A. Fidar, F. Memon, and D. Butler, "Environmental implications of water efficient microcomponents in residential buildings," *Science of the total environment,* vol. 408, pp. 5828-5835, 2010.

[73] J. Y. C. Leong, K. S. Oh, P. E. Poh, and M. N. Chong, "Prospects of hybrid rainwater-greywater decentralised system for water recycling and reuse: A review," *Journal of cleaner production,* vol. 142, pp. 3014-3027, 2017.

[74] S. O. Ajayi, L. O. Oyedele, M. Bilal, O. O. Akinade, H. A. Alaka, H. A. Owolabi*, et al.*, "Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements," *Resources, Conservation and Recycling,* vol. 102, pp. 101-112, 2015.

[75] J.-L. Gálvez-Martos, D. Styles, H. Schoenberger, and B. Zeschmar-Lahl, "Construction and demolition waste best management practice in Europe," *Resources, conservation and recycling,* vol. 136, pp. 166-178, 2018.

[76] N. F. Arenas and M. Shafique, "Reducing embodied carbon emissions of buildings–a key consideration to meet the net zero target," *Sustainable Futures,* vol. 7, p. 100166, 2024.

[77] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, "Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review," *Renewable and sustainable energy reviews,* vol. 29, pp. 394-416, 2014.

[78] F. Pomponi and A. Moncaster, "Reducing embodied carbon in the built environment: A research agenda," 2016.

[79] J. M. Allwood, M. F. Ashby, T. G. Gutowski, and E. Worrell, "Material efficiency: providing material services with less material production," *Philosophical transactions of the royal society a: mathematical, physical and engineering sciences,* vol. 371, 2013.

[80] F. Asdrubali and G. Grazieschi, "Life cycle assessment of energy efficient buildings," *Energy Reports,* vol. 6, pp. 270-285, 2020.

[81] F. Pomponi and A. Moncaster, "A theoretical framework for circular economy research in the built environment," in *Building information modelling, building performance, design and smart construction*, ed: Springer, 2017, pp. 31-44.

[82] P. De Wilde, "The gap between predicted and measured energy performance of buildings: A framework for investigation," *Automation in construction,* vol. 41, pp. 40-49, 2014.

[83] S. Azhar, W. A. Carlton, D. Olsen, and I. Ahmad, "Building information modeling for sustainable design and LEED® rating analysis," *Automation in construction,* vol. 20, pp. 217-224, 2011.

[84] C. D. Roa, S. Schiavon, and T. Parkinson, "Targeted occupant surveys: A novel method to effectively relate occupant feedback with environmental conditions," *Building and Environment,* vol. 184, p. 107129, 2020.

[85] M. Santamouris, "Innovating to zero the building sector in Europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change," *Solar Energy,* vol. 128, pp. 61-94, 2016.

[86] A. Vilches, A. Garcia-Martinez, and B. Sanchez-Montañes, "Life cycle assessment (LCA) of building refurbishment: A literature review," *Energy and Buildings,* vol. 135, pp. 286-301, 2017.

[87] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy and buildings,* vol. 40, pp. 394-398, 2008.

[88] K. Amasyali and N. M. El-Gohary, "A review of data-driven building energy consumption prediction studies," *Renewable and Sustainable Energy Reviews,* vol. 81, pp. 1192-1205, 2018.

[89] H. Lund, P. A. Østergaard, P. Sorknæs, S. Nielsen, I. R. Skov, M. Yuan*, et al.*, "District heating in clean energy systems," *Nature Reviews Clean Technology,* vol. 1, pp. 532-546, 2025.

[90] W. O'Brien, F. Tahmasebi, R. K. Andersen, E. Azar, V. Barthelmes, Z. D. Belafi*, et al.*, "An international review of occupant-related aspects of building energy codes and standards," *Building and environment,* vol. 179, p. 106906, 2020.

[91] U. Iyer-Raniga and J. P. C. Wong, "Evaluation of whole life cycle assessment for heritage buildings in Australia," *Building and Environment,* vol. 47, pp. 138-149, 2012.

[92] H. Yuan and L. Shen, "Trend of the research on construction and demolition waste management," *Waste management,* vol. 31, pp. 670-679, 2011.

[93] X. Dou, F. Ren, M. Q. Nguyen, A. Ahamed, K. Yin, W. P. Chan*, et al.*, "Review of MSWI bottom ash utilization from perspectives of collective characterization, treatment and existing application," *Renewable and Sustainable Energy Reviews,* vol. 79, pp. 24-38, 2017.

[94] R. T. Lima, P. Couto, and T. F. Bastos, "Buildings Sustainability Certifications and the Common European Framework Level (s)," in *International Conference on Recovery, Maintenance and Rehabilitation of Buildings*, 2023, pp. 496-507.

[95] I. Sartori, A. Napolitano, and K. Voss, "Net zero energy buildings: A consistent definition framework," *Energy and buildings,* vol. 48, pp. 220-232, 2012.

[96] F. Pomponi, C. De Wolf, and A. Moncaster, "Embodied carbon in buildings," *Springer Int Publishing AG,* vol. 20, pp. 443-460, 2018.

[97] G. Habert, M. Röck, K. Steininger, A. Lupísek, H. Birgisdottir, H. Desing*, et al.*, "Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions," *Buildings & Cities,* vol. 1, pp. 429-452, 2020.

[98] D. Ürge-Vorsatz and S. T. Herrero, "Building synergies between climate change mitigation and energy poverty alleviation," *Energy policy,* vol. 49, pp. 83-90, 2012.

[99] M. O. Alfadil, M. A. Kassem, and R. A. Al-Mansob, "Renewable Energy Integration for Net-Zero Buildings: Challenges, Opportunities, and Strategic Pathways," *Buildings,* vol. 16, p. 879, 2026.

[100] A. Abdeen, W. O'Brien, B. Gunay, G. Newsham, and H. Knudsen, "Comparative review of occupant-related energy aspects of the National Building Code of Canada," *Building and Environment,* vol. 183, p. 107136, 2020.

[101] T. Lützkendorf and D. Lorenz, "Capturing sustainability-related information for property valuation," *Building Research & Information,* vol. 39, pp. 256-273, 2011.

[102] S. Röck, L. Kleinheinz, and J. Walde, "Assessing Measurement Invariance of Subjective Well-Being Across European Countries," *Journal of Happiness Studies,* vol. 27, p. 37, 2026.

[103] L. Tupenaite, I. Lill, I. Geipele, and J. Naimaviciene, "Ranking of sustainability indicators for assessment of the new housing development projects: Case of the Baltic States," *Resources,* vol. 6, p. 55, 2017.

[104] R. Said, M. N. Daud, Z. Esha, R. A. Majid, and M. Najib, "Owners' perception towards sustainable housing affordability in Kuching, Sarawak," *Journal of Design and Built Environment,* pp. 194-206, 2017.

[105] S. O. Ajayi, L. O. Oyedele, M. Bilal, O. O. Akinade, H. A. Alaka, and H. A. Owolabi, "Critical management practices influencing on-site waste minimization in construction projects," *Waste management,* vol. 59, pp. 330-339, 2017.

[106] S. O. Ajayi, L. O. Oyedele, O. O. Akinade, M. Bilal, H. A. Alaka, and H. A. Owolabi, "Optimising material procurement for construction waste minimization: An exploration of success factors," *Sustainable materials and technologies,* vol. 11, pp. 38-46, 2017.

[107] Malaysian Standard, "Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings – Code of Practice (Third Revision)," MS 1525:2019, 2019.

[108] Ministry of Energy, Green Technology and Water, Malaysia, "National Green Technology Policy," 2009.

[109] Ministry of Energy, Green Technology and Water, Malaysia, "Green Technology Master Plan Malaysia 2017–2030," 2017.

[110] Economic Planning Unit, Prime Minister's Department, Malaysia, "National Energy Policy 2022–2040," 2022.

[111] Ministry of Economy, Malaysia, "National Energy Transition Roadmap (NETR)," 2023.

[112] Ministry of Natural Resources, Environment and Climate Change, Malaysia, "National Climate Change Policy 2.0," 2024.

[113] Suruhanjaya Tenaga, Malaysia, "National Energy Efficiency Policy and Action Plan (NEAAP) 2.0 (2026–2035)," 2026.

[114] Government of Malaysia, "Energy Efficiency and Conservation Act 2024 (Act 861)," 2024.

[115] Government of Malaysia, "Energy Efficiency and Conservation Regulations 2024," 2024.

[116] Government of Sarawak, "Environment (Reduction of Greenhouse Gases Emission) Ordinance 2023 (Chapter 85)," 2023.

[117] Ministry of Energy and Environmental Sustainability Sarawak (MEESty), "Energy and Environmental Sustainability Policy and Governance Framework," Sarawak.