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Research article

A Comprehensive Literature Review on Greenhouse Gas Mitigation in Thailand's Building and Industrial Sectors: Technical, Economic, and Policy Insights from Recent Studies

Jirawong Siribrahmanakul[1*], and Somying Ngarmpornprasert[1]

[1] College of Engineering and Technology, Dhurakij Pundit University, Bangkok, 10210, Thailand
* Correspondence: j.siribrahmanakul@gmail.com; somying.ngt@dpu.ac.th

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Abstract: This scoping review examines greenhouse gas (GHG) mitigation options in Thailand's industrial and building sectors, synthesizing findings from 26 peer-reviewed articles and five national policy documents. The review is structured around three themes: technical viability, financial performance, and policy alignment of key mitigation strategies. Results indicate that energy-efficiency retrofitting, renewable energy integration, carbon capture and storage (CCS), and life-cycle assessment (LCA)-guided design – particularly when combined with Building Information Modeling (BIM) – can substantially reduce both operational and embodied emissions. Many of these approaches demonstrate strong financial attractiveness, characterized by high internal rates of return (IRR) and short payback periods. However, widespread deployment remains constrained by policy fragmentation, insufficient incentive mechanisms, and weak stakeholder coordination. The review also exposes critical gaps in sectoral strategies, including the absence of tailored energy conservation measures for certain building typologies. The limited uptake of local green certification schemes, such as TREES, which cover fewer than 15% of certified green buildings nationwide, further reflects structural barriers in Thailand's regulatory and market environments. To address these challenges, this study proposes a sectoral strategy matrix that maps appropriate technologies to specific building types alongside relevant economic indicators. It also recommends harmonizing existing frameworks – EEP2015, AEDP2015, and BEC2021 – with Thailand's 2022 Nationally Determined Contribution (NDC) and Long-Term Low Emissions Development Strategy (LT-LEDS). Future research should explore integrated models incorporating ESG criteria, stakeholder capacity-building, and carbon tracking linked to Science-Based Targets (SBTs). By bridging technical rigor with policy relevance, this review offers actionable guidance for researchers, policymakers, and industry practitioners.

Keywords: Energy efficiency; carbon mitigation; life cycle assessment; science-based targets; Thailand

1. Introduction

Climate change mitigation has become a priority in modern society, forcing national governments and industries to adopt more effective GHG-reduction policies aligned with scientific advice. The paths for global warming levels adopted at 1.5°C and 2.0°C – defined in the Paris Agreement and advocated by programs like Science-Based Targets (SBTs) – call for immediate action from all industries, with a focus on decarbonization. In Thailand, where industrial and building energy use accounts for a major share of the country's total emissions, effective action in these areas is not only a critical environmental imperative but also a potential economic opportunity. The industry sector accounts for nearly 40% of Thailand's total emissions, mostly from fossil fuel combustion [1]. In contrast, the building sector, including residences, offices, retail buildings, and public institutions, accounts for approximately 15% of emissions, primarily from electricity consumption for cooling, lighting, and operations [2]. This is further supported by office LCA studies that highlight high operational loads, particularly HVAC and lighting [3]. These figures characterize the imperative for effective, scalable mitigation measures.

To address these issues, Thailand has put forward a series of policies for energy and climate, including the Energy Efficiency Plan (EEP2015) [4], Alternative Energy Development Plan (AEDP2015) [5], Power Development Plan (PDP2015) [6], and Building Energy Code (BEC2021) [7]. In addition, the Energy Conservation Promotion Act B.E.2535 (1992) [8] has created a long-term legislative foundation for energy conservation measures. Furthermore, Thailand has recently committed to updated international goals under the 2022 Nationally Determined Contribution (NDC) and the Long-Term Low Emissions Development Strategy (LT-LEDS), reinforcing the need to integrate new strategies for deep decarbonization. However, even with the strength of these tools, they require revision to capture advancements in technology, innovative financial instruments, and global climate targets. For one, policies currently on the books often aim to reduce energy use; yet they don't incorporate life-cycle emissions data, carbon trading schemes, or harmonization between private-sector activities and Net Zero targets. Previous academic studies have put forward numerous mitigation measures that include energy efficiency retrofitting improvements, integration with renewable energy technologies, carbon capture and storage (CCS) technologies, and design principles based on life cycle assessment (LCA), often supplemented with digital tools like Building Information Modeling (BIM) [3, 9, 10, 11, 12]. While they provide estimates of both technical and economic aspects, limited academic work connects these findings with Thailand's evolving policy and institutional environment.

This review consolidates evidence from 26 peer-reviewed research articles and five official policy documents to examine the intersection of technical feasibility, economic viability, and policy relevance in Thailand's efforts to reduce GHG emissions.

2. Methodology

This study employed a scoping literature review approach to synthesize measures for reducing GHG emissions in Thailand's construction and industrial sectors. The review aimed to link technological knowledge with economic feasibility and policy harmonization, thereby facilitating the identification of replicable, context-appropriate strategies for national application.

2.1 Literature Selection

A total of 26 peer-reviewed scholarly articles published between 2006 and 2024 were selected based on predefined inclusion criteria. These criteria included (1) direct relevance to GHG mitigation, (2) application within Thailand's building or industrial sectors, (3) inclusion of quantitative or model-based findings, and (4) publication in peer-reviewed journals. The 2006–2024 timeframe was chosen to reflect the evolution of Thailand's energy and climate frameworks, covering both the pre-Paris Agreement period and the post-BEC2021 implementation context. This allowed the review to capture shifts in technology availability, policy direction, and methodological practice over time, including the emergence of BIM-LCA and SBTi-aligned studies in the 2020s. To mitigate selection bias, articles were identified through a combination of database search (ScienceDirect, SpringerLink, TCI), backward reference tracking, and citation-based relevance filtering. The screening was performed independently using the stated criteria to ensure consistency and thematic saturation across the sample. In parallel, five national-level policy documents were selected based on their legal status, current applicability, and foundational role in shaping Thailand's energy and climate strategies. These include the Energy Efficiency Plan (EEP2015) [4], the Alternative Energy Development Plan (AEDP2015) [5], the Power Development Plan (PDP2015) [6], the Building Energy Code (BEC2021) [7], and the Energy Conservation Promotion Act B.E.2535 (1992) [8]. While other planning documents, such as Thailand's NDC and National Climate Change Master Plan, exist, they were not included due to their non-binding nature or insufficient detail for building-sector implementation at the time of writing. In alignment with the PRISMA-ScR framework, the initial search process involved querying Scopus and ThaiJo databases using a combination of keyword strings, including: "greenhouse gas mitigation," "GHG reduction," "building sector," "industrial sector," "energy efficiency," "carbon neutrality," "carbon capture and storage," "life cycle assessment," "BIM," and "Thailand." Boolean operators (AND, OR) were used to enhance the sensitivity and specificity of search results. This process identified 223 articles from Scopus and 13 from ThaiJo. After removing duplicates and conducting an initial screening of titles and abstracts, 108 articles were selected for full-text assessment. Finally, 26 articles were retained for synthesis based on relevance, methodological rigor, and alignment with the inclusion criteria (Figure 1).

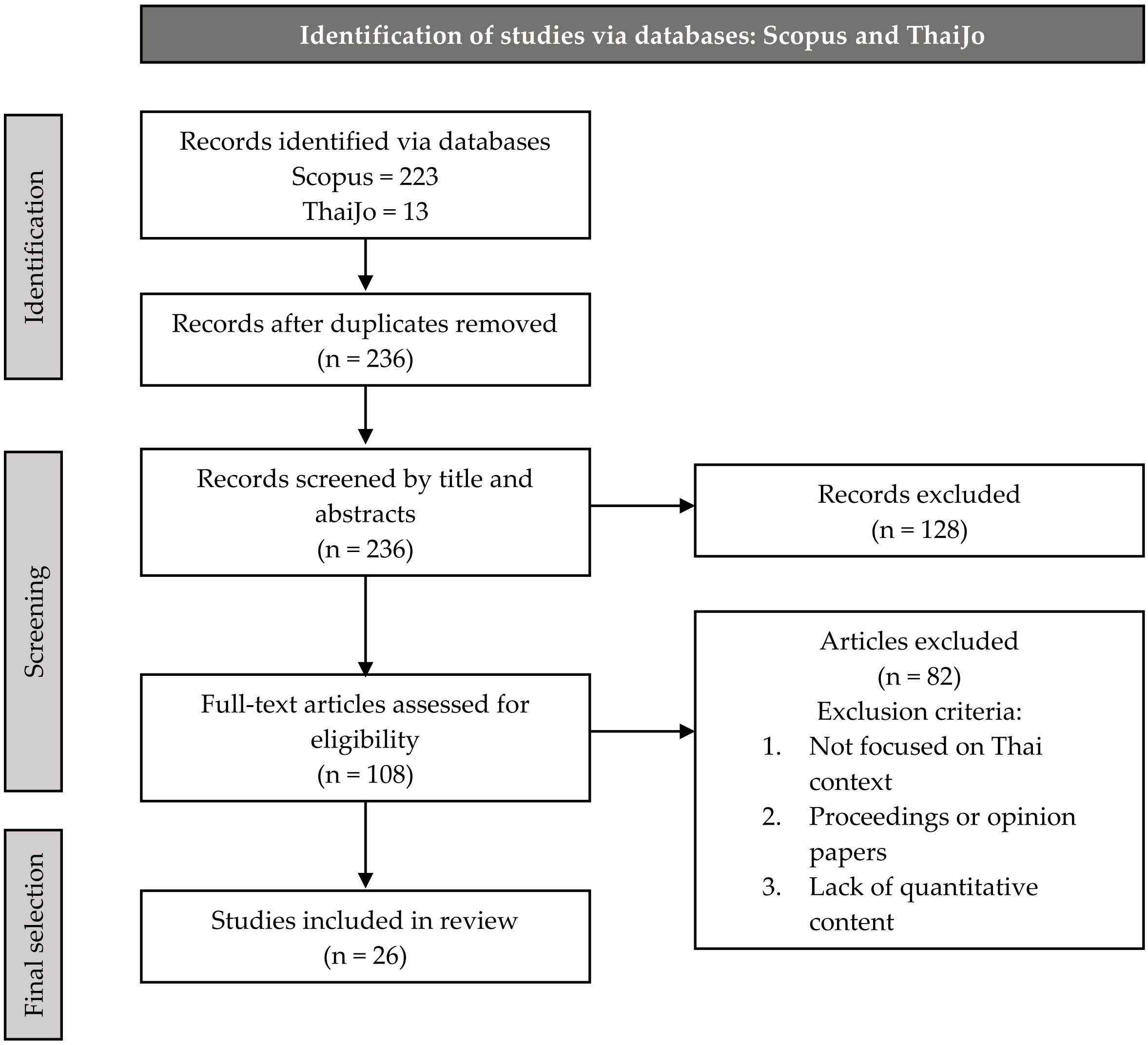

Figure 1. PRISMA-ScR flow diagram illustrating the identification, screening, and selection process of articles for inclusion in the scoping review.

2.2 Classification and Summary of Literature

Table 1 provides a structured summary of the 26 academic articles that were analyzed, including information on year of publication, methodologies applied, sector focus, and breadth of analysis. The articles were categorized based on underlying methodologies, including:

- Life Cycle Assessment (LCA)
- Energy simulation and modeling (e.g., LEAP, CGE)
- Techno-economic analysis
- Policy assessment or scenario-based modeling

These methodological groupings were used to understand not only the scope of technical and economic findings but also the kinds of questions each approach is suited to address. For example, LCA studies generally emphasized embodied versus operational carbon tradeoffs, while LEAP and CGE models captured system-level implications and macroeconomic outcomes. Techno-economic and sensitivity analyses focused on financial feasibility, while policy modeling helped to frame alignment with national and international targets. This categorization informed subsequent data extraction and thematic synthesis, ensuring that each mitigation approach was assessed across multiple dimensions: technical effectiveness, financial feasibility, and policy relevance.

2.3 Data Extraction and Grouping

Quantitative measures such as energy savings, percentage decrease in GHG emissions, IRR, payback time, and marginal abatement cost (MAC) were obtained from individual studies. Likewise, qualitative remarks regarding implementation barriers, policy deficiencies, and stakeholder concerns were also noted.

Data from each article were extracted into structured tables and matrices to enable comparison across metrics and methods.

It was categorized in terms of thematic dimensions in accordance with their main contributions:

- Technical effectiveness of specific measures (e.g., HVAC retrofits, rooftop PV, CCS)
- Economic performance and financial viability
- Regulatory frameworks and institutional readiness

This thematic clustering was essential for identifying performance trends, context-dependent barriers, and sector-specific policy implications, which were subsequently integrated into the comparative synthesis presented in the Results section.

2.4 Analytical Synthesis Approach

The synthesis procedure consisted of two main phases:

1. Comparative Analysis: Different tools were analyzed with respect to what they specifically address (e.g., Life Cycle Assessment for embodied carbon and LEAP for long-term national scenarios). Similarities and distinctions between these tools were noted to identify how different tools complement one another. This phase enabled identification of methodological strengths, data limitations, and sector-specific insights, which informed the structure of the final comparative synthesis across strategies.
2. Policy Integration Mapping: The findings from the technical-economic analysis were aligned with the five main national policies [4 - 8] to identify gaps and potential avenues for strategic alignment. This also included considering how mitigation measures could enable Thailand's transition to Net Zero, as well as determining where future modeling should align with methodologies such as the Science Based Targets initiative (SBTi). Rather than employing a rigid, systematic protocol, the synthesis followed a structured scoping review process that enabled thematic integration across technical, financial, and policy domains.

Table 1. Summary of Reviewed Articles by Year, Method, and Focus.

Reference	Author (s) / Year	Methodology	Sector Focus	Analytical Scope
[1]	Pradhan et al. (2022)	LCA+BIM	Housing	Early-stage carbon optimization
[2]	Tangprasert & Leeprechanon (2023)	LEAP	Industry	LEAP scenario analysis
[3]	Kofoworola & Gheewala (2009)	LCA	Office Buildings	Embodied & Operational emissions
[9]	Tevis et al. (2019)	Scenario modeling	Residential	Behavioral scenarios
[10]	Viriyaroj et al. (2024)	GHG accounting	Industry	Carbon footprint estimation
[11]	Tulevech et al. (2018)	Techno-economic	Industry	Energy-cost trade-off
[12]	Inharwararak & Stravoravdis (2023)	Techno-economic	Industry	BEMS & lighting systems
[13]	Kofoworola & Gheewala (2008)	LCA	Office Building	Embodied & Operational emissions
[14]	Phyo Zaw Oo et al. (2021)	LCA	Materials	Low-carbon cement
[15]	Seeley & Dhakal (2021)	Policy review	Policy	Energy law analysis
[16]	Ananwattanaporn et al. (2021)	LCA + GHG inventory	Industrial Buildings	EF benchmarking
[17]	Yamtraipat et al. (2006)	LCA	Residential	Life cycle GHG evaluation
[18]	Jareemit et al. (2022)	Policy analysis	Policy	Policy coherence
[19]	Boonpanya & Masui (2020)	Policy review	Policy	Power sector strategy
[20]	Rajbhandari et al. (2019)	LCA	Buildings	Material intensity hotspots
[21]	Thepkhun et al. (2013)	Policy evaluation	Policy	Implementation barriers
[22]	Kongwanarat & Limmeechokchai (2016)	Techno-economic	Industrial	Investment decision modeling
[23]	Limmeechokchai et al. (2024)	Techno-economic	Industry	Efficiency adoption modeling
[24]	Rajbhandari & Limmeechokchai (2020)	LEAP	Residential	Long-term energy demand
[25]	Limmeechokchai et al. (2017)	Energy simulation	Commercial Buildings	Cooling energy modeling
[26]	Chaichaloempreecha et al. (2019)	LEAP + MAC modeling	Multi-sector Policy	National Plan Scenario Modeling
[27]	Lohmeng et al. (2017)	Policy Review	Certification	Green Building Rating Systems
[28]	Rahong & Prapaspongsa (2022)	LCA	Construction	Green materials innovation
[29]	Inazumi et al. (2011)	Environmental Accounting	Urban Waste	Waste Stream GHG Accounting
[30]	Limmeechokchai et al. (2023)	Policy analysis	Policy	Policy incentive analysis
[31]	Saranrom et al. (2023)	Scenario modeling	Residential	Technology adoption & policy

3. Literature Review

3.1 Embodied Carbon and Life Cycle Assessment (LCA)

Recent years have seen growing scholarly interest in applying Life Cycle Assessment (LCA) to quantify embodied carbon in buildings, aiming to capture the hidden GHG footprint associated with materials and the construction stage, not just operational use. This subsection reviews key LCA studies across Thailand's building typologies and interprets their implications for decarbonization strategies. The use of Life Cycle Assessment (LCA) to assess embodied carbon in Thailand's construction industry has shown a continued upward trend in research activity. LCA provides a structured methodology for assessing cumulative greenhouse gas (GHG) emissions associated with building operations and material changes throughout a building's life cycle. A series of studies investigated embodied emissions across different building types, construction phases, and energy systems. Kofoworola and Gheewala [3] performed one of the earliest LCA-oriented analyses of a typical office building in Bangkok. They found that embodied emissions from concrete and steel accounted for a significant share of the overall life-cycle contribution. Subsequent research by the same authors [13] on a larger commercial building validated that these materials continue to dominate the embodied carbon footprint. For industrial buildings, Tulevech et al. [11] conducted a multi-scenario LCA study of a low-energy facility. The results showed that approximately 71% of total emissions originated from embodied energy, while operational energy contributed only 17%. This trend was similarly observed in the residential sector by Viriyaroj et al. [10], who found that operational emissions accounted for 72–78% of total life-cycle GHGs in standard detached houses, while embodied emissions comprised 19–23%, primarily from concrete and insulation. The study done by Tevis et al. [9] involved a life cycle assessment (LCA) of different alternative energy supply scenarios for office buildings. The study showed that rooftop photovoltaic (PV) systems with ice thermal storage could reduce reliance on grid electricity by up to 38%, while the strategy might increase metal depletion and resource use in upstream activities. Under the design integration framework, Inharwararak and Stravoravdis [12] used a Building Information Modeling–Life Cycle Assessment (BIM-LCA) approach to examine a low-rise residential complex in Thailand. The study findings revealed that material optimization at early stages, using BIM software, resulted in a 42.4% reduction in embodied emissions. To enhance methodological accuracy in Thai-specific contexts, Phyo Zaw Oo et al. [14] proposed a localized set of normalization factors for LCA. These country-specific metrics were developed to improve the comparability and relevance of LCA results, particularly when applied to construction systems and material supply chains in Thailand. While both Tulevech et al. [11] and Viriyaroj et al. [10] used LCA to evaluate life-cycle emissions, their findings differ substantially – one emphasizes embodied emissions, the other operational emissions. This discrepancy is likely due to differences in building type, system boundary, and occupancy assumptions. Industrial facilities often have large structural footprints with low energy loads, while residential homes have lighter construction but high cooling demands. Furthermore, the modeling boundary (e.g., cradle-to-gate vs cradle-to-grave) and assumed usage profiles significantly affect the outcome. More broadly, methodological limitations were observed across studies. Not all LCA models used the same emission factors or normalization methods; some relied on global datasets, while others incorporated region-specific parameters. Only one study [14] proposed Thai-specific normalization factors. This inconsistency limits cross-comparability of results and weakens policy translation. Additionally, BIM-LCA integration remains in the early stages, with limited adoption beyond academic pilots. Despite these limitations, the reviewed LCA studies consistently highlight the carbon dominance of concrete and steel in embodied emissions and underscore the mitigation potential of early design intervention, material optimization, and locally adapted emission factors.

Table 2. Summary of Key Findings from LCA Studies in Thailand.

Study Focus	Sector	Main Findings & Implications	Reference
Office Building LCA (Bangkok)	Commercial	Operational energy (HVAC ~56%, lighting ~15%) is dominant; high embodied emissions from concrete (64%) and steel (17%)	[3]
Operational Energy Supply (Office)	Commercial	Rooftop PV with ice thermal storage reduced grid dependency (~38%); caution metal depletion impacts	[9]
Standard Residential Houses	Residential	Operational emissions dominate life-cycle (72–78%); notable embodied emissions (19–23%)	[10]
Low-Energy Industrial Buildings	Industrial	Embodied energy (materials ~71%) exceeds operational energy (~17%); renewables and recycled materials are recommended	[11]
BIM-LCA for Housing Estates	Residential	Early design integration of BIM-LCA reduces embodied emissions by ~42.4%	[12]
Office Building LCA (Extended)	Commercial	Embodied emissions dominated by concrete and steel; findings consistent with earlier Bangkok office study [6]	[13]
Thai Normalization Factors	General	Development of Thai-specific normalization factors enhances the accuracy and applicability of local LCAs	[14]

3.2 Energy Use and GHG Emission Reduction in Thailand's Building Sector

An increasing number of studies in Thailand have been investigating energy conservation and GHG mitigation strategies in the building sector. These studies primarily focus on retrofitting existing systems, enhancing energy efficiency in commercial and residential buildings, and integrating renewable energy solutions such as photovoltaic (PV) systems. The reviewed articles assessed technical performance, financial viability, and regulatory alignment, particularly in relation to the Building Energy Code (BEC2021). Seeley and Dhakal [15] analyzed HVAC and lighting system retrofits in commercial buildings and reported energy savings of approximately 18.1%, an internal rate of return (IRR) of 19%-20%, and a payback period of 4 years. Ananwattanaporn et al. [16] evaluated BEC-compliant retrofits in low-rise residential buildings and found energy savings of approximately 49.4%, with an IRR of 19.3% and a payback period of 4.36 years. Yamtraipat et al. [17] showed that increasing indoor temperature setpoints from 24°C to 26°C in offices reduced electricity usage by 12.3%, offering a no-cost behavioral mitigation option. Jareemit et al. [18] explored Zero Energy Office Building (ZEB) investment and confirmed its strong financial viability, particularly when supported by dedicated incentives and policy mechanisms. Tevis et al. [9] found that rooftop PV systems with thermal storage reduced grid electricity reliance by 38% in commercial buildings, though metal depletion impacts were noted. Across these studies, retrofit interventions in residential buildings yielded higher energy savings than in commercial settings, due in part to lower baseline efficiency and greater insulation potential in detached housing stock. However, commercial retrofits demonstrated superior financial indicators (e.g., IRR, payback) due to economies of scale and operating hour advantages. Collectively, these findings suggest that retrofit strategies must be customized by building type, with residential retrofits focusing on thermal performance and envelope measures, while commercial buildings may prioritize HVAC system upgrades and control systems. Policy incentives should reflect these differences to maximize return on investment and GHG reductions.

Table 3. Summary of Key Findings from Energy Efficiency and Renewable Energy Studies in Thailand's Building Sector.

Study Focus Group	Building Type	Main Findings and Economic Implications	Reference
Renewable Energy Integration (PV)	Commercial & Residential	Rooftop PV reduced grid dependency by ~38% and is economically viable with appropriate incentives.	[9]
HVAC and LED Retrofits	Commercial	Average energy savings ~18.1%; IRR ~19–20%; payback period ~4 years	[15]
Residential Retrofits (BEC compliance)	Residential	Energy savings up to ~49.4%; IRR ~19.3%; payback period ~4.36 years	[16]
Indoor Temperature Setpoint Adjustments	Commercial (Offices)	Increasing temperatures from 24°C to 26°C reduced energy consumption ~12.3% nationwide	[17]
Zero Energy Office Buildings (ZEB)	Commercial	Integration of renewable energy and energy-efficient design is highly economically viable with policy support	[18]

Note: Table includes only empirical or techno-economic studies with measured or modeled outcomes.

3.3 GHG Reduction in the Industrial and Commercial Sectors through Energy Efficiency and CCS Technologies

Several studies have examined the prospects for GHG mitigation in Thailand's commercial and industrial sectors through advanced energy efficiency measures and carbon capture and storage (CCS) technology. These options are typically assessed for both technical potential and economic viability, particularly in light of the nation's changing policy environment and long-term decarbonization objectives. Seeley and Dhakal [15] studied retrofitting energy efficiency measures in a range of commercial buildings. Their study focused on heating, ventilation, and air conditioning (HVAC) systems, lighting upgrades, and building energy management systems (BEMS). Their results showed that operational energy savings were around 18%, with internal rates of return (IRR) of 19%-20%, a payback period of about 4 years, and negative marginal abatement costs ranging from –68.9 to –87 USD per tonne of CO_2 equivalent. Boonpanya and Masui [19] used a Computable General Equilibrium (CGE) model to assess the macroeconomic effects of CCS deployment in Thailand's industry. From their study, it was observed that applying CCS reduced marginal carbon abatement costs from around USD 186/tCO_2eq to USD 69/tCO_2eq. The model also estimated decreased GDP losses under stringent emissions targets, suggesting enhanced economic resilience. Rajbhandari et al. [20] carried out a long-run CGE-based scenario analysis of the joint impact of energy efficiency and CCS in industry. In the absence of a mitigation policy, GDP losses may reach 22.5% under stringent emission constraints. Nevertheless, the joint implementation of CCS and efficiency technologies reduced estimated GDP losses to 7%, revealing their significance in protecting economic stability in pursuit of mitigation objectives. Despite promising model projections, the number of peer-reviewed studies on CCS in Thailand remains limited, and no large-scale commercial facilities currently exist. Most literature relies on hypothetical modeling rather than demonstration-scale analysis. Moreover, CCS is not explicitly included in current Thai energy plans such as EEP2015, AEDP2015, or PDP2015. While the Long-Term Low Emission Development Strategy (LT-LEDS) mentions CCS as a potential mitigation option post-2037, its implementation will depend heavily on regulatory support, infrastructure readiness, and international financing mechanisms.

Table 4. GHG Mitigation Strategies and Economic Impact in Industrial and Commercial Sectors.

Mitigation Measure	Sector	Key Findings	Economic Indicators	References
Energy Efficiency Retrofits (HVAC, LED, BEMS)	Commercial	Operational energy reduction ~18%	IRR ~19–20%, short payback (~4 yrs), negative marginal abatement costs (-68.9 to -87 USD/tCO_2eq)	[15]
Carbon Capture and Storage (CCS)	Industrial	Industrial emissions reduction ~20–30% (based on CGE model)	Reduction in carbon abatement cost from ~USD186 to USD69/tCO_2eq	[19]
Integrated CCS & Energy Efficiency	Industrial	Substantial emission reductions (CGE scenario analysis)	Mitigates macroeconomic GDP loss (from ~22.5% to ~7%) under strict emission targets	[20]

3.4 Economic and Social Impact Assessment of GHG Reduction Measures Using CGE and LEAP Models

Recent GHG mitigation literature in Thailand has used macroeconomic and energy planning models, such as Computable General Equilibrium (CGE) and Long-range Energy Alternatives Planning (LEAP), to analyze the economic and social co-benefits of mitigation trajectories. The models have been used to analyze policy scenarios, measure marginal abatement costs, and estimate impacts on GDP, energy security, and public health. Boonpanya and Masui [19] employed a CGE model to study the economy-wide implications of GHG mitigation policies in 2030. They found that adopting CCS lowered marginal abatement costs from USD 186 to USD 69 per tCO_2eq and greatly alleviated GDP losses in high-reduction scenarios. In a similar CGE-based analysis, Rajbhandari et al. [20] found that GDP losses could reach 22.5% in the absence of mitigation but were contained at about 7% with combined CCS and energy efficiency. These results suggested the macroeconomic benefit of technology bundling under long-term reduction goals. Thepkhun et al. [21] utilized a CGE model to replicate Thailand's Low-Carbon Scenario 2050. They found through their analysis that mitigation actions across sectors could reduce GHG emissions by as much as 281.7 $MtCO_2$eq by 2050, while preserving long-run economic growth. Concurrently, the LEAP model has been implemented in several sectoral studies. Kongwanarat and Limmeechokchai [22] evaluated Nationally Appropriate Mitigation Actions (NAMAs) in the Thai residential sector. The analysis suggested negative marginal abatement costs (–13.13 to –4.09 USD/tCO_2 eq), in addition to rural energy access and public health benefits. Limmeechokchai et al. [23] introduced a system-level LEAP model, focusing on the significance of urban-level mitigation. Their research determined the contribution of building energy systems to Thailand's urban decarbonization potential. Rajbhandari and Limmeechokchai [24] and Limmeechokchai et al. [25] together assessed Thailand's mitigation pathways under the Paris Agreement through LEAP and CGE hybrid scenarios. They identified that, in the absence of advanced technologies, long-term emissions cuts would not meet the 1.5°C pathway and would entail high economic costs. Chaichaloempreecha et al. [26] compared Thailand's national energy plans with NDC targets. The simulations using the LEAP model highlighted the contribution of energy efficiency and renewable energy policies in bridging the gap between prevailing national trends and global commitments. While these models provide valuable system-level insights, they also entail methodological limitations. CGE models typically assume perfect market equilibrium and may overlook micro-level behavioral responses, spatial heterogeneity, and institutional inertia. LEAP models are data-intensive and depend heavily on assumed scenario inputs, which introduces uncertainty and reduces transferability across contexts. Neither model accounts for non-quantifiable barriers such as stakeholder resistance or policy implementation lags. Therefore, while these tools are valuable for national-level planning and long-range strategy, they should be complemented with empirical data, stakeholder engagement, and multi-scalar validation to support the translation of real-world policies.

Table 5. Economic and Social Impacts from CGE and LEAP Model Assessments in Thailand.

Analytical Model	Sector Focus	Key Findings and Economic Indicators	Socio-Economic Co-benefits	References
CGE Model	National (2030 NDCs)	CCS integration reduces carbon abatement cost (from USD186 to USD69/tCO_2eq), GDP losses significantly mitigated	Enhanced economic resilience, lower economic disruption, improved energy security	[19]
CGE Model	Long-term National scenarios (2050)	Without advanced technologies, GDP losses ~22.5%; CCS and efficiency technologies reduce GDP losses to ~7%	Economic stability, resilience under stringent GHG targets	[20]
CGE Model	National low-carbon pathway (2050)	Mitigation potential up to 281.7 MtCO_2eq by 2050 while maintaining economic growth	Long-term energy security, sustainable economic development	[21]
LEAP Model	Residential NAMAs	Negative marginal abatement costs (-13.13 to -4.09 USD/tCO_2eq), economically attractive	Improved rural energy security, better public health	[22]
LEAP Model	Urban systems	Building energy systems contribute significantly to the potential for urban decarbonization.	Reduced urban emissions, improved air quality	[23]
LEAP Model	National mitigation pathways (Paris targets)	Technology-limited scenarios fail to meet the 1.5°C pathway; advanced technologies reduce system costs.	Avoided economic burden, improved policy feasibility	[24,25]
LEAP Model	National energy plans vs NDC	Energy efficiency and renewable policies narrow the gap between PDP/EEP and NDC targets.	Policy coherence, improved national energy security	[26]

3.5 Green Building Standards and Certification in Thailand

Thailand has, in the past decade, adopted green building rating systems to promote environmentally friendly construction and energy-efficient architectural design. A variety of standards, including internationally recognized systems such as LEED, regionally established systems such as Singapore's Green Mark, and Thailand's local Thai Rating of Energy and Environmental Sustainability (TREES), have been studied regarding their application, benefits, and obstacles in the Thai context. According to Lohmeng et al. [27] (as of 2017), the U.S.-based LEED system was the most widely adopted in Thailand, with an estimated rate of about 56%, due to its international acceptance and market recognition. LEED-certified buildings typically achieved 20% to 40% savings in operational energy and were linked to lower GHG emissions and better environmental performance. Singapore's Green Mark system, while regionally specific, was implemented in around 32% of certified projects in Thailand. The system achieved energy savings of 20% to 35% and provided greater flexibility for tropical climates. It, however, had medium complexity and medium localization for Thai building practices. TREES, developed by the Thai Green Building Institute, was used in fewer than 15% of all projects certified in Thailand. Although the system was localized to suit domestic conditions and exhibited comparable potential energy and GHG savings to LEED and Green Mark (between 20% and 40%), lower adoption was due to the absence of mandatory requirements, low public awareness, and a lack of government incentives. As the certification landscape may have evolved since 2017, future studies should revisit adoption rates and investigate the effectiveness of policies and financial instruments in promoting localized systems such as TREES.

Table 6. Comparison of Green Building Certification Systems in Thailand.

Certification System	Origin	Adoption in Thailand (%)	Key Benefits	Major Barriers	Reference
LEED	USA (International)	~56%	High global recognition, significant operational energy savings (20–40%), and GHG emission reductions	Higher certification cost, procedural complexity	[27]
Green Mark	Singapore (Regional)	~32%	Regional recognition, notable energy savings (20–35%)	Moderate complexity, limited local adaptation	[27]
TREES	Thailand (Local)	<15%	Tailored to local conditions, significant potential for energy and emission reductions (20–40%)	Limited market awareness, insufficient governmental incentives	[27]

Note: Adoption rates and comparisons are based on data from Lohmeng et al. [27], published in 2017.

3.6 Application of BIM in Building Design for Environmental Impact Reduction

Building Information Modeling (BIM) is a digital approach that enables more informed building design and construction decision-making. Within the context of environmental impact minimization, BIM can be coupled with Life Cycle Assessment (LCA) to detect and minimize embodied carbon at an early stage of design. The integration of BIM and LCA is generally referred to as BIM-LCA. Inharwararak and Stravoravdis [12] conducted one of the limited number of studies in Thailand that applied the BIM-LCA method to an actual residential development. The research assessed the environmental performance of a low-rise housing estate by incorporating material quantity information from BIM into LCA software. The analysis at the early design stage facilitated comparisons of embodied GHG emissions across various construction scenarios. The findings indicated that the application of BIM-LCA at the initial design stage resulted in a 42.4% decrease in embodied emissions relative to traditional baseline practices. Aside from the quantitative effect, the research also identified qualitative advantages, including increased accuracy in material estimation, greater transparency in environmental reporting, and improved compliance with certification systems. Despite its benefits, the study recognized several barriers to the widespread adoption of BIM-LCA in Thailand. Included among these barriers were the high initial costs of software and training, a lack of experienced professionals, and limited availability of localized environmental datasets for assessing material impacts. Despite its benefits, the study noted several barriers to the widespread adoption of BIM-LCA in Thailand. These included high initial software and training costs, a shortage of qualified professionals, and limited availability of localized environmental datasets for material impact assessment. While Inharwararak and Stravoravdis [12] offer a promising case study, peer-reviewed BIM-LCA research in Thailand remains scarce. No other comprehensive studies were found in the review period (2006–2024), highlighting a significant research gap. Adoption appears constrained by a lack of regulatory incentives, limited awareness, and the absence of standardized BIM-LCA frameworks in national policy. Future research should prioritize pilot projects in commercial or public buildings, assess institutional readiness, and evaluate potential pathways for integrating BIM-LCA into regulatory mechanisms such as the Building Energy Code or TREES certification systems.

Table 7. Benefits, Barriers, and Recommendations for BIM-LCA Adoption in Thailand

Aspect	Key Findings	Reference
Benefits	Early design-stage integration reduces embodied emissions (~42.4%), improves data accuracy, and simplifies environmental certification compliance.	[12]
Barriers	High initial cost of software/training, lack of local expertise, and insufficient localized environmental databases for accurate assessments.	[12]
Recommendations	Provide targeted governmental financial incentives, expand professional training programs, develop comprehensive localized databases, and integrate BIM-LCA into national building codes and policy frameworks.	[12]

Note: All entries are based on a single peer-reviewed study [12], the only known BIM-LCA publication in Thailand during the review period (2006–2024).

4. Results and Discussion

The literature review identifies a variety of greenhouse gas (GHG) mitigation options in Thailand's building and industrial sectors. Although many have explored technical feasibility, cost-effectiveness, and policy environment separately, none have presented a cross-sector synthesis of what is best, under what circumstances, and for which type of building. Table 8 summarizes the most promising mitigation options by technical effectiveness, economic viability, and practical preparedness across three primary sectors: residential, commercial, and industrial. Among the reviewed strategies, energy efficiency retrofits consistently demonstrated the highest short-term financial returns, with IRRs ranging from 19% to 20% and payback periods of approximately four years [15, 16]. Renewable energy solutions such as rooftop PV and thermal storage can achieve operational GHG reductions of 30% to 45%, depending on system configuration and building type [9, 28]. CCS exhibited the highest long-term mitigation potential (~20–30% emissions reduction), but required large-scale investments and policy intervention to reduce marginal abatement costs [19, 20]. BIM-LCA integration and material substitutions delivered reductions of up to 42.4% and 71%, respectively, in embodied carbon, but remain limited by data availability and the lack of regulatory frameworks [3, 11, 12].

Notwithstanding the reported success of a range of strategies, several implementation barriers persist. In the residential sector, research rarely examines behavior-related drivers (e.g., occupant involvement, appliance use). Commercial building research frequently focuses on retrofit technologies but does not discuss the operationalization of financial incentives at scale. In industrial settings, although CCS is promising, few studies incorporate actual stakeholder capacity, technology readiness, or grid-level interactions. Furthermore, the majority of studies prioritize mitigation results (e.g., energy efficiency, emissions abatement) without adequately examining institutional or financial mechanisms necessary to bring these solutions to scale. Few works [2, 18, 26] discuss Thailand's policy landscape and its alignment (or lack thereof) with long-run decarbonization pathways. None of them systematically examines how private-sector entities can align their operations with frameworks such as the Science Based Targets initiative (SBTi) or ESG reporting. The absence of stakeholder-led localized assessments is another serious shortfall. The current literature insufficiently addresses the perceptions and uptake of these strategies by government agencies, construction developers, regional planners, and end users. As Thailand increasingly moves toward its Net Zero ambitions, future research should go beyond technical roadmaps to examine the dynamics of institutional capacity building, stakeholder engagement, and policy implementation. A number of studies also point to data limitations—e.g., unavailability of region-specific emission factors, cost databases, and digital infrastructure—especially regarding BIM-LCA, GHG accounting, and marginal abatement cost modeling. These issues hinder wider adoption and cause bottlenecks in standard-setting and implementation. In summary, while technical potential exists across multiple strategies, scaling impact requires a coordinated approach involving financial policy instruments, local data infrastructure, and stakeholder alignment mechanisms. Sector-specific tailoring of incentives, integration of SBTi-aligned carbon tracking, and bridging institutional capacity gaps should be prioritized in Thailand’s next phase of decarbonization policy.

Table 8. Synthesis of Key GHG Mitigation Measures, Economic Feasibility, and Socio-Economic Co-benefits.

Mitigation Strategy	Sector	Technical Effectiveness & GHG Reduction (%)	Economic Feasibility (IRR, Payback)	Socio-Economic Co-benefits	References
Sustainable Material Choices (Bio-based, Recycled)	Building, Industrial	Embodied emissions reduction (~38–71%)	Cost-effective through material substitution	Reduced environmental impacts, resource efficiency	[3,11]
Renewable Energy (PV, Thermal Storage)	Commercial, Industrial	Operational GHG reduction (~38–45%) depending on scenario and building type	IRR ~15–19.3 %, Payback ~4–6 yrs	Improved air quality, reduced fossil fuel dependency	[9,18,28]
BIM-LCA Integration	Building	Embodied carbon reduction (~42.4%)	High initial investment, feasible with incentives	Accurate design optimization, streamlined certification	[12]
Energy Efficiency (HVAC, LED, BEMS)	Commercial, Residential	Energy savings (~18–49%), GHG reduction (~20–40%)	IRR ~19–20%, Payback ~4 yrs	Enhanced energy security, economic resilience	[15,16]
Carbon Capture and Storage (CCS)	Industrial	Industrial emissions reduction (~20–30%) (model-based)	Reduced abatement costs (USD 186→69/tCO_2eq)	Economic resilience, minimized GDP losses	[19,20]

Note: Values represent reported ranges from empirical or model-based studies reviewed; effectiveness varies by building type, system boundary, and scenario assumptions.

5. Conclusion

This review combined 26 peer-reviewed papers with five national policy reports on options for reducing greenhouse gas (GHG) emissions from buildings and industry in Thailand. The evidence shows that several measures, such as energy-efficiency refurbishment, building-integrated rooftop photovoltaics (PV), carbon capture and storage (CCS), sustainable building material selection, and Building Information Modeling-integrated life-cycle assessments (BIM-LCA), demonstrate high technical performance and economic efficacy. The above strategies have been proven to generate energy reductions of 18% to 49%, reduce embodied carbon emissions by up to 71%, and provide substantial co-benefits, including increased energy security, better health outcomes for populations, and greater macroeconomic resilience. Despite the availability of viable technologies and frameworks, significant implementation challenges persist. Key constraints include insufficient financial incentives, fragmented policy implementation, high upfront investment costs, and limited access to standardized environmental data at the national level. Moreover, Thailand's current policy architecture - anchored in EEP2015, AEDP2015, and BEC2021 - requires strategic updating to better align with evolving climate targets and technological pathways. Existing policy instruments do not yet systematically incorporate embodied carbon metrics, advanced modeling tools, or explicit linkages to international frameworks such as the Science Based Targets initiative (SBTi). To advance Thailand's decarbonization agenda, future efforts should focus on three interlinked priorities. Institutional and stakeholder capacity-building: Stakeholders—ranging from policymakers and architects to developers and regulators—must be equipped with the skills, tools, and training to implement and manage decarbonization strategies effectively. This includes education in BIM-LCA, GHG inventory systems, and low-carbon procurement. The integration of ESG and carbon accounting frameworks: Public and private organizations should align their construction and industrial development with ESG frameworks, Science-Based Targets, and test carbon accounting methods to boost credibility and attract green investments. Such alignment is particularly crucial for large infrastructure and property portfolios. Data-driven policy and regulatory evolution: Existing energy and building regulations should be updated to explicitly include embodied carbon assessment, digital design requirements (e.g., BIM-based compliance pathways), and life cycle-based performance benchmarks. Establishing national databases for emission factors, retrofit performance, and marginal abatement costs would substantially improve policy design and implementation effectiveness. This review is subject to several limitations. The analysis relies exclusively on peer-reviewed academic literature and official policy documents, which may underrepresent recent practitioner-led initiatives or unpublished pilot projects. In addition, some emerging areas—such as BIM-LCA integration and CCS deployment—remain supported by only a limited number of Thailand-specific empirical studies, thereby constraining the generalizability of the findings. In conclusion, Thailand's pathway to achieving its 1.5–2.0°C climate targets will depend not only on available technologies but also on the systems that govern, monitor, and scale them. A coordinated approach combining technical innovation, policy reform, financial incentives, and stakeholder engagement will be essential to achieving measurable, lasting GHG reductions.

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