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Strategic Framework for Driving Thai Universities toward Net-Zero Emission: A Case Study of Khon Kaen University

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ABSTRACT

The transition of higher education institutions toward carbon neutrality has become an important component of national climate strategies. In Thailand, although several universities have begun conducting greenhouse gas (GHG) inventories, significant gaps remain in Scope 3 accounting, monitoring systems, and strategic planning frameworks that support long-term decarbonization. This study develops an integrated strategic framework to guide universities toward net-zero pathways, using Khon Kaen University (KKU) as a case study. A mixed-methods approach was employed, combining a systematic literature review, gap analysis, emissions clustering, and design-factor synthesis aligned with international standards, including the IPCC Guidelines, the GHG Protocol Corporate Standard, and ISO 14064-1. Data from Thai university reports and national emission factors were analyzed to classify institutions using hierarchical clustering based on energy intensity, emission intensity per student, sequestration capacity, and commuting emissions. The results reveal that Scope 3 emissions—particularly commuting and procurement—remain insufficiently reported across many institutions, limiting comparability but representing a major mitigation opportunity. The study proposes a University Net Zero Planning Tool that integrates emissions inventories, clustering-based benchmarking, and a design-factor matrix linking emission drivers to prioritized interventions. Application to KKU demonstrates both high operational emissions and substantial land-based sequestration potential. The framework offers a transferable decision-support model for universities in developing-country contexts seeking structured pathways toward carbon neutrality and net-zero targets.

HIGHLIGHTS

- Framework combining a systematic review and clustering to chart net-zero paths.
- Highlights gaps in Scope 3 emissions and MRV that hinder carbon reduction.
- Groups universities into four clusters based on energy, transport, and waste.
- Synthesizes intervention factors and strategic variables into a planning tool.
- Applies the framework to Khon Kaen University and propose a net-zero path.

1. INTRODUCTION

Climate change is one of the most urgent crises of the 21st century, disrupting economies, ecosystems, and societies. The accumulation of greenhouse gases (GHGs), primarily carbon dioxide, accelerates global warming and amplifies vulnerabilities. The Paris Agreement (UNFCCC, 2015) set a target to limit global temperature rise to well below 2°C, with efforts to remain within 1.5°C above pre-industrial levels. Meeting these goals requires participation beyond governments, extending to higher education institutions (HEIs), which play a vital role in sustainability transitions (Husic, 2024).

Universities are increasingly conceptualized as "campus-as-city" systems, with interlinked domains of energy, mobility, waste, water, and land use (Kohl et al., 2022; Abo-Khalil, 2024; Naaman et al., 2024; Buntornwon and Kumphong, 2022; Filho et al., 2023). They act both as contributors to emissions and as testbeds for low-carbon solutions. Recent studies have reinforced this dual role, showing how systematic frameworks can guide zero- carbon planning. For

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example, Wang et al. (2023) proposed a systematic design framework for zero-carbon campuses that emphasizes cross-domain integration, while Islam et al. (2023) highlighted campus-based zero-carbon action plans as accelerators of citywide decarbonization. Similarly, Paredes-Canencio et al. (2024) reviewed the carbon footprints of higher education institutions globally, underscoring persistent gaps in Scope 3 emissions and MRV systems.

In Thailand, several universities have begun to articulate institution-level climate targets and campus sustainability programs. For example, Chulalongkorn University has publicly communicated a net-zero GHG ambition by 2050, while Mahidol University has articulated a "9-to-Zero" pathway aiming at net-zero emissions by 2030. Some institutions have also begun developing digital platforms for monitoring their carbon footprints. However, no prior study integrates clustering and design-factor synthesis. Despite this momentum, common constraints remain across the sector: Scope 3 categories are often incomplete (especially commuting and procurement), monitoring systems are fragmented across units, and institutions lack a consistent benchmarking framework aligned with national targets of carbon neutrality by 2050 and net zero by 2065 (ONEP, 2021). This study responds to calls for more robust MRV integration (Helmers et al., 2021; Lin et al., 2024) and financial feasibility assessments (Li and Jia, 2022). It contributes both theoretically and practically to pathways toward carbon-neutral universities.

Against this backdrop, our study contributes a Thai-contextualized planning framework that integrates (i) a structured synthesis of global evidence, (ii) driver-based clustering to reflect institutional heterogeneity, and (iii) an MRV-ready set of design factors and strategic variables that can be operationalized as a replicable tool for Thai universities beyond a single case.

2. METHODOLOGY

2.1 Research design

This study employed a mixed-methods research design (Okoro, 2023), integrating both qualitative and quantitative approaches to ensure methodological rigor and practical relevance. The research framework, shown in Figure 1, was organized into seven sequential phases. The first phase involved a systematic literature review (SLR) to establish theoretical foundations and identify best practices worldwide. Next, a gap analysis was conducted to pinpoint methodological and contextual gaps relevant to Thai universities. The third phase synthesized design factors by pinpointing key variables influencing greenhouse gas (GHG) emissions and strategic planning. In the fourth phase, a university clustering approach grouped institutions into comparable categories based on size, functions, and emission profiles. The fifth phase identified GHG drivers and conducted a SWOT analysis to assess institutional strengths and weaknesses. Building on these insights, the sixth phase developed a process template to serve as a replicable roadmap for universities seeking to achieve net-zero targets. Finally, the framework was tested through a case study of Khon Kaen University (KKU), confirming its robustness and relevance. Overall, this design ensures that the study is grounded in global theory while being tailored to the specific context of Thai higher education.

2.2 Systematic literature review

This review followed the PRISMA 2009 guidelines and Kitchenham's protocol, covering Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. Peer-reviewed studies (2000-2025) on GHG accounting, net-zero pathways, and sustainability frameworks were synthesized, highlighting methods such as the ecological footprint for low-carbon campuses (Zheng et al., 2021) and emission-reduction strategies in higher education institutions (Aghamolaei and Fallahpour, 2023).

Universities are increasingly seen as 'small-scale models of cities,' serving as testing grounds for low-carbon transitions (Guerrieri et al., 2019). This campus-as-city viewpoint positions higher education institutions as microcosms of urban sustainability, where infrastructure transitions and urban-metabolism flows across energy, water, materials, and waste can be examined through integrated operations, infrastructure, and governance (Kennedy et al., 2011; Bulkeley et al., 2014). Empirical examples show a variety of methodologies: assessments of energy, transportation, and waste in Indonesian universities (Ridhosari and Rahman, 2020); carbon sequestration from campus green spaces in the U.S. (Fox et al., 2020); and comparative studies of retrofitting versus zero-energy buildings in Europe and the U.S. (Del Borghi et al., 2021). These highlight the importance of context-sensitive approaches to decarbonization.

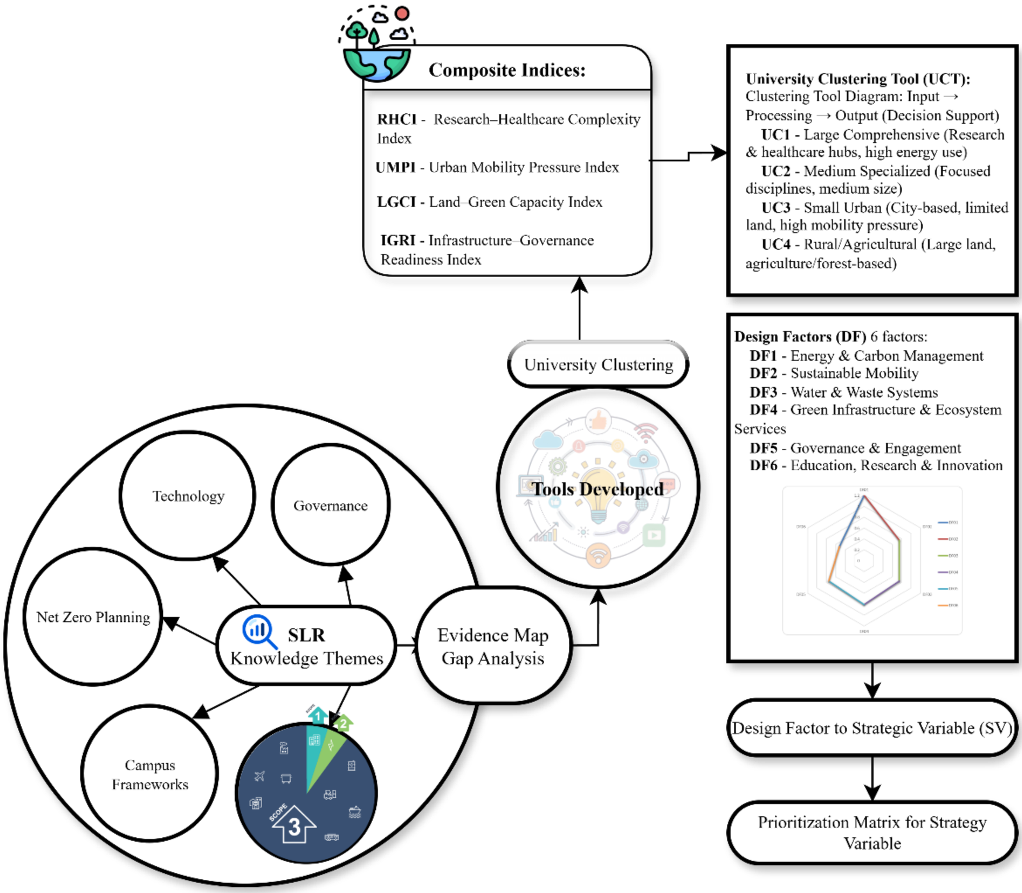

Figure 1. Research design diagram

Systematic reviews offer deeper insights: Zubair et al. (2023) provided structured CO_2 measurement frameworks; Guerrieri et al. (2019) emphasized the role of universities as transitional hubs in urban decarbonization; and nature-based strategies that incorporate green and blue infrastructure were identified as crucial for resilience (Depietri and McPhearson, 2017; Wang et al., 2022).

The SLR procedure and thematic distributions are summarized in Table 3. To strengthen relevance for developing country contexts, we additionally coded studies by data availability and MRV maturity, highlighting recurring constraints in Scope 3 data collection and verification capacity.

Taken together, the evidence confirms that universities act as innovation hubs for sustainability, supporting the clustering and comparative approach used in this research. This combined knowledge directly contributes to the study's goal: to develop and test a framework to evaluate institutional strengths and weaknesses and guide strategic efforts toward net-zero universities.

2.3 Data collection and analysis

Quantitative data were collected from institutional reports, including the Thailand Greenhouse Gas Management Organization (TGO) and the Provincial Electricity Authority (PEA). Indicators covered energy consumption, fuel use, waste generation, green space, and commuting surveys. Cluster analysis was performed using Ward's method, validated with the Calinski-Harabasz index. Factor analysis was carried out using PCA with varimax rotation.

For the clustering analysis (Table 1), we compiled an institutional dataset covering N Thai universities (N=11) for the fiscal year 2012-2020. The clustering variables were selected to represent (i) operational scale, (ii) energy and mobility pressures, and (iii) mitigation potential, and included: electricity use intensity (kWh/m²·year), total organizational emissions (tCO_2e/year), emission intensity (tCO_2e/population·year), campus area (ha), and a sequestration indicator (tCO_2e/year) derived from a green-land inventory. All continuous variables were z-standardized prior to clustering to avoid scale dominance. Hierarchical agglomerative clustering was conducted using Ward's linkage with Euclidean distance. The number of clusters (k) was determined by maximizing the Calinski-Harabasz index and cross-checking against silhouette scores shown in Table 2, yielding k=4 as the most parsimonious and statistically supported solution.

Table 1. Dataset, variables, and clustering methodology

Parameter	Technical description
Sample Size (N)	11 Higher Education Institutions (HEIs)
Time Period	2012-2023 (Based on availability of CFO reports)
Primary Variables	Scope 1, 2, 3 Emissions; Total Population; Campus Area; Hospital Dummy
Composite Indices	RHCI, UMPI, LGCI, IGRI (Derived from physical and emission data)
Data Source	Institutional Sustainability Reports, CFO Research Papers, TGO Database
Standardization	Z-score Transformation (Mean=0, Std. Dev=1)
Distance Metric	Euclidean Distance
Clustering Algorithm	Ward's Hierarchical Clustering Method
k Selection Criteria	Calinski-Harabasz Index (CHI) and Average Silhouette Coefficient
Missing Data Handling	Scope 3: Group Mean Imputation based on Peer Cluster Characteristics

Organizational and operational boundaries follow the GHG Protocol. Emissions are reported by Scope 1-3 and by major activity categories. Emission factors were sourced from national factors and complemented by IPCC guidance where local factors were unavailable. The reporting structure and data-quality statements follow the ISO 14064-1 standard.

Because Scope 3 reporting is not uniformly available across institutions, we separated the analysis into (i) a core clustering model using variables with complete (or near-complete) coverage across universities, and (ii) an extended clustering model incorporating Scope 3-related indicators only for the subset with reported data. We report the core model as the primary classification for national benchmarking and discuss the implications of Scope 3 data gaps as a limitation and a source of uncertainty.

Table 2. Cluster validity Indices across k-values

Number of clusters (k)	Calinski-Harabasz Index (CHI)	Average Silhouette score	Cluster interpretation
2	16.45	0.41	Poor separation; High intra-cluster variance
3	21.12	0.52	Significant overlap between Regional and Urban groups
4	28.7	0.61	Optimal; Best structural representation
5	24.35	0.54	Overfitting; Identifying single-member clusters

2.4 Tool synthesis process

Building on the structured synthesis steps outlined in Figure 1, we created an integrated planning tool. The synthesis process involved (i) extracting design factors from both international and local literature, (ii) consolidating indicators from emission accounting protocols, (iii) mapping these indicators into functional areas (energy, mobility, waste, land, governance), and (iv) developing a Decision Support Template that links GHG sources, metrics, and interventions. The process was iterative, including expert validation workshops and pilot testing with institutional data. The result is the University Net Zero Planning Tool, which allows for clustering universities by profile, quantifying their Scope 1-3 emissions, and identifying feasible interventions.

Methodologically, we follow the GHG Protocol to define organizational and operational boundaries and classify emissions into Scopes 1-3, while calculation and reporting requirements are structured in accordance with ISO 14064-1. Emission factors and methodological choices are aligned with IPCC guidance and nationally endorsed factors where available. This standards-based approach strengthens comparability and supports third-party verification and future MRV system integration.

Strategic Variables (SVs) were defined as actionable institutional levers mapped to each Design

Factor (DF) domain and GHG scope (Scope 1-3). To ensure reproducibility, each SV was quantified through a two-step procedure. First, SV scores were derived from a structured multi-criteria rating exercise in which experts assessed (a) expected mitigation impact, (b) implementation feasibility, and (c) time-to-delivery. Criterion weights were defined a priori, and the composite SV score was calculated as a weighted sum and then normalized within each DF domain to enable comparison across domains.

Second, the potential GHG reduction for each SV (tCO_2e/year) was estimated using activity data and emission factors consistent with the defined system boundary. For technology-based actions (e.g., PV, retrofits, EV fleets). For governance and behavioral SVs (e.g., procurement policies, travel management), reductions were estimated using conservative uptake scenarios and sensitivity ranges.

2.5 Case study selection

KKU was selected for its size (880 hectares), diverse operations, and its declared net zero 2040 roadmap. The choice is important for three reasons. First, it is among the largest regional universities in Thailand, functioning like a micro-city with its own hospitals, dormitories, academic units, and transportation systems. Second, its net zero 2040 goal offers an ambitious standard for other Thai institutions. Third, KKU's large green spaces and sequestration potential (~18,000 tCO_2e/year) make it well-suited for testing the balance between emissions and offsets. These factors align with recommendations from global reviews emphasizing the importance of diverse campus profiles for validating net-zero frameworks (Paredes-Canencio et al., 2024; Wang et al., 2023).

3. RESULTS AND DISCUSSION

3.1 Literature review outcomes

Out of 5,400 initial studies, 525 met the criteria. Dominant themes were carbon accounting (40%), campus frameworks (25%), net-zero planning (20%), technology and innovation (10%), and governance (5%), as shown in Table 3. These align with recent reviews (Paredes-Canencio et al., 2024), which highlight the urgent need to expand Scope 3 coverage and establish MRV standards. Research gaps remain, especially in integrating digital MRV tools (Helmers et al., 2021) and ensuring feasibility through financial analysis (Li and Jia, 2022).

Tree-based carbon sequestration is a significant yet often under-evaluated part of campus greenhouse gas (GHG) inventories. A study at the University of Georgia estimated the carbon stored in live trees on its main campus, showing measurable reductions in institutional emissions (Fox et al., 2020). This underscores the importance of the Infrastructure and Green Ratio Index (IGRI), developed within our clustering framework, which highlights the role of green cover in enhancing carbon balance. For agricultural and suburban universities, this factor is especially critical, as larger campus landscapes offer a unique chance for nature-based sequestration strategies.

To improve the clustering framework, four synthetic driver indices were created to represent the structural emission factors of universities shown in Figure 2. Shown: Research and Healthcare Intensity (RHCI), University Mobility Pressure Index (UMPI), Laboratory and Governance Carbon Intensity (LGCI), and Infrastructure and Green Ratio Index (IGRI). These indices help distinguish university clusters by highlighting different emission profiles. For example, urban flagships often exhibit higher UMPI and LGCI scores due to commuting pressures and intensive laboratory work, whereas agricultural universities tend to have high IGRI scores because of their large green areas and potential offsetting effects.

Table 3. Major themes from the SLR on University GHG Management

Theme	Focus areas	Share of studies
GHG Management and Carbon Accounting	Scope 1-3 inventories, EF development, quantification methods	40%
Green Campus Frameworks	UI Green Metric, eco-campus benchmarking	25%
Net Zero Strategic Planning	Institutional roadmaps, transition policies	20%
Technology and Innovation	Renewable energy, EV mobility, wastewater-to-energy	10%
Governance and Stakeholder Engagement	Policy frameworks, participatory governance	5%

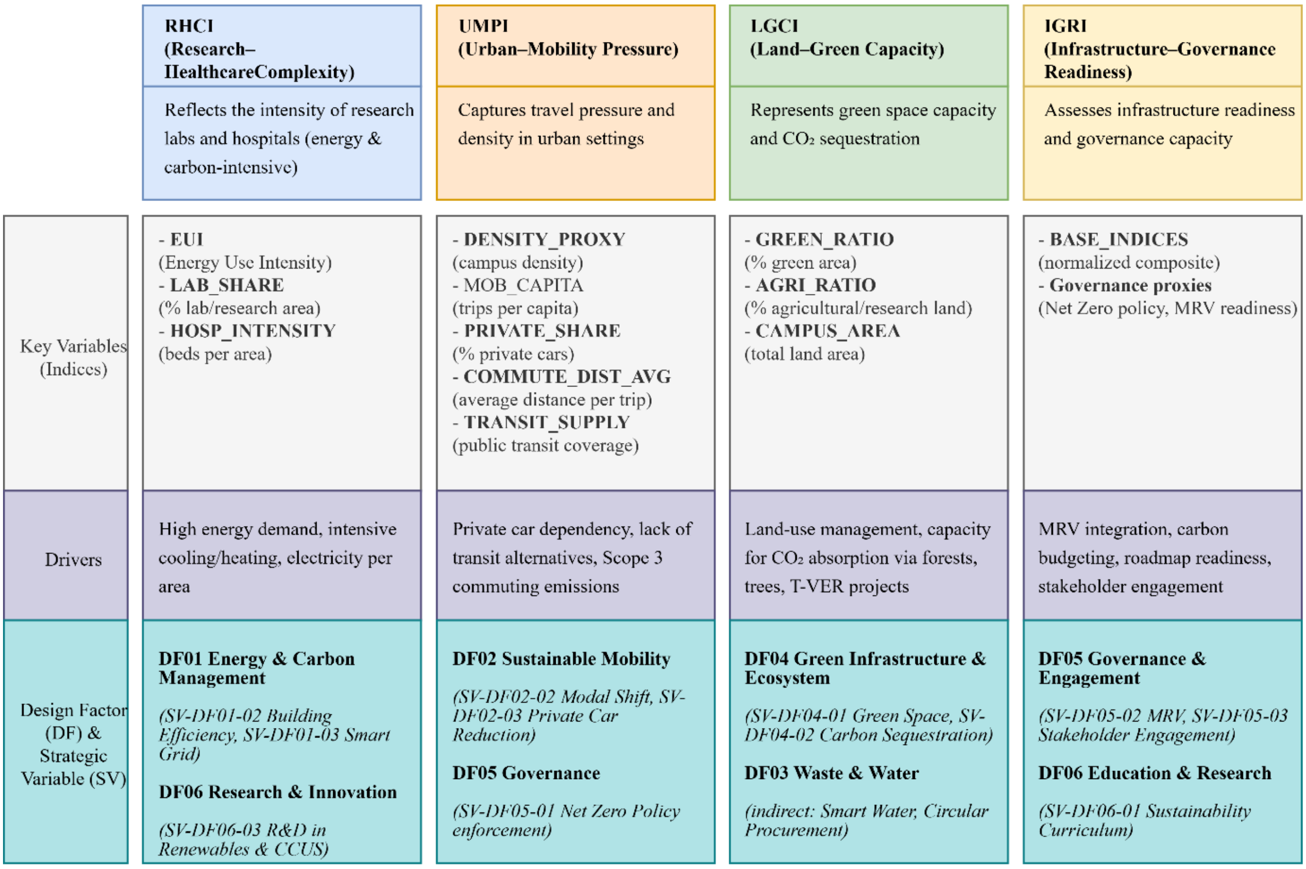

Figure 2. Synthetic driver indices and clustering structure

3.2 Emissions baselines and university clustering

Thai universities were grouped into four clusters: (1) urban flagships with high emissions intensity, (2) regional comprehensives like KKU with moderate intensity and high sequestration, (3) smaller suburban universities with moderate profiles, and (4) agricultural universities with high sequestration potential. The indicators applied include Energy Use Intensity (kWh/m²/year), Emission Intensity per student (tCO_2e/student/year), Sequestration Index (tCO_2e/hectare/year), and Commuting Emission Share (% of total emissions). The clustering framework enables benchmarking across institutions and prioritization of interventions based on context-specific profiles, consistent with empirical approaches by Lin et al. (2024) and Helmers et al. (2021). The results are summarized in Table 4, which compares annual emissions, campus size, emission intensity, and sequestration proxies across the four clusters.

Rather than labeling clusters by institutional type, we define them by observable operational profiles. For instance, Cluster 3 represents smaller, teaching-focused campuses with lower energy intensity and limited research/healthcare functions. Importantly, Rajabhat universities appear in multiple operational profiles; therefore, we do not treat 'Rajabhat' as a proxy for low emissions. Within-cluster dispersion (SD and range) is reported to reflect heterogeneity.

The heatmap analysis (Figure 3) illustrates the distribution of strengths and weaknesses across the four university clusters. These findings align with studies on land-use optimization in Chinese urban contexts, which emphasize the need to balance expansion and sustainability (Wang et al., 2022). Additionally, lessons from carbon-neutral campus building projects in Europe and the United States highlight the trade-offs between retrofitting existing facilities and designing new zero-energy buildings (Del Borghi et al., 2021). Together, these insights reinforce the practical utility of the clustering model in identifying tailored pathways for different university archetypes.

Table 4. Annual institutional emissions, campus scale, and sequestration potential

Cluster	Cluster 1: Urban flagship	Cluster 2: Regional comprehensive	Cluster 3: Urban/smaller	Cluster 4: Agricultural/green
Annual emissions (tCO_2e/year)	~140,000	~125,000	~40,000	~60,000
Campus size (ha)	300	880	600	1,500
Emissions intensity (tCO_2e/ha)	467.00	142.00	67.00	40.00
Sequestration capacity (tCO_2e/year)	2,500	18,000	6,000	25,000
Normalized emissions (0-100)	100	89	29	43
Normalized sequestration (0-100)	10	72	24	100

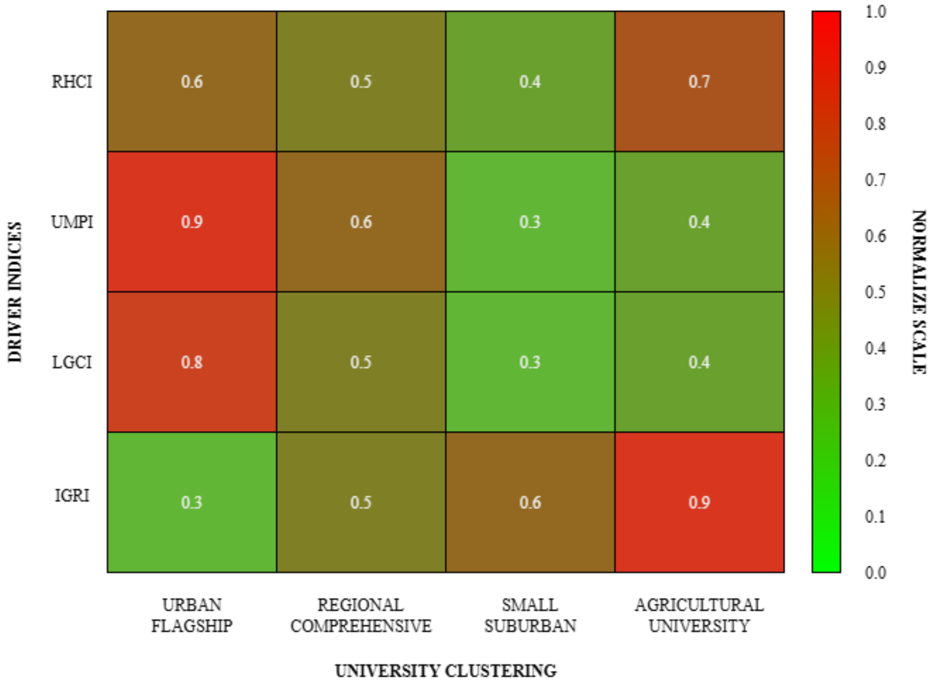

Figure 3. Heatmap-relationship of driver indices and university clustering

3.3 Design factor matrix

Six domains define the design factors: Built and Energy, Mobility, Waste, Water, Land Use, and Governance. Each domain links indicators to interventions:

- Built and Energy: retrofit index (% of buildings upgraded), renewable energy fraction (%), energy efficiency ratio (kWh/m²).
- Mobility: modal shift index (% shift from private vehicles), EV adoption rate (% of campus fleet), commuting emission per capita ($kgCO_2e$/person).
- Waste: recycling ratio (% of waste recycled), waste-to-energy conversion rate (%), composting efficiency.
- Water: water reuse rate (%), wastewater treatment efficiency (%).
- Land Use: green space per capita (m²/person), sequestration factor (tCO_2e/hectare).
- Governance: policy integration index (0-5 scale), MRV maturity score (1-4 levels).

This structured matrix follows models proposed by Wang et al. (2023) and Aghamolaei and Fallahpour (2023), ensuring measurable pathways for net-zero planning.

3.4 Comparative international insights

Drawing on peer-reviewed articles published between 2020 and 2025, we compare KKU's profile with international patterns. A recent global review of higher education carbon footprints (Paredes-Canencio et al., 2024) shows that Scope 3 sources (commuting, procurement, food, and waste) often dominate campus emissions, especially in developing regions with high reliance on private vehicles. This aligns with KKU's inventory, where commuting and procurement are significant contributors. Methodologically, Helmers et al. (2021) emphasize the importance of transparent system boundaries and harmonized MRV, while Zheng et al. (2021) demonstrate how ecological footprint-based accounting can complement traditional GHG inventories. Both approaches reinforce our call for a digital MRV backbone.

Case-based empirical studies further highlight differences. Lin et al. (2024) employ the emission-factor method at Zhejiang Ocean University, demonstrating how campus-specific activity data (electricity, fuels, waste) and local factors significantly impact the results. Our clustering approach follows this logic by categorizing Thai universities according to their emission intensity and sequestration capacity. Li and Jia (2022) examine the feasibility of achieving campus carbon neutrality, focusing on financial constraints and operational trade-offs. Our results support the need to emphasize internal pricing and investment signals alongside technical upgrades.

In terms of strategic design, Wang et al. (2023) propose a systematic, cross-domain framework (energy, mobility, buildings, operations) that mirrors our design factor architecture, while Aghamolaei and Fallahpour (2023) synthesize actionable measures (efficiency retrofits, demand management, renewables, and circularity) consistent with the interventions prioritized for KKU. Islam et al. (2023) position campus action plans as catalysts for city-scale transitions, which reinforces KKU's role as a regional "living lab," where EV transit, wastewater-to-biogas, and nature-based sequestration can scale beyond campus boundaries.

Taken together, the 2020-2025 literature converges on three comparative insights relevant to KKU: (i) Scope 3 management and MRV harmonization are decisive (Helmers et al., 2021; Paredes-Canencio et al., 2024), (ii) context specific factorization of activity data and localized emission factors are essential for credible baselines (Zheng et al., 2021; Lin et al., 2024), and (iii) integrated, cross-domain frameworks paired with feasible financing and governance instruments are prerequisites for credible net- zero pathways (Wang et al., 2023; Li and Jia, 2022; Aghamolaei and Fallahpour, 2023; Islam et al., 2023).

3.5 Case study: KKU

Khon Kaen University (KKU) was analyzed as a model of a campus-as-city system, reflecting the interlinked dynamics of energy, transport, waste, water, and land use. The case illustrates both the strengths and constraints of a large Thai regional university and demonstrates how design factors and strategic variables can guide tailored net-zero planning.

To contextualize KKU's profile, we benchmark its EUI and emissions intensity against published campus inventories and the Thai sample range. We further test sensitivity to the grid emission factor and commuting assumptions to determine whether KKU's pattern is typical for regional comprehensive universities or driven by case-specific factors (e.g., hospital demand share).

KKU consumes more than 102 million kWh of electricity annually, with the hospital complex alone accounting for nearly 40% of demand. The university's Electricity Use Intensity (EUI) ranges between 250-300 kWh/m²·year, significantly above international benchmarks (150-200 kWh/m²·year), reflecting Thailand's hot climate and dependence on air conditioning.

- Scope 1 emissions: derived from LPG, refrigerants, and campus vehicles.
- Scope 2 emissions: dominated by purchased electricity, forming the largest share of the carbon footprint.
- Scope 3 emissions: commuting and procurement remain underreported, with private vehicles responsible for more than 70% of daily trips.

Using the cluster-based framework, KKU (Cluster 2: Regional Comprehensive) reported ~125,000 tCO_2e annually across its 880-ha campus. This corresponds to a moderate emissions intensity (≈approximately 142 tCO_2e/ha). Importantly, with more than 60% of land designated as green or agricultural zones—including a 240-ha restored dry dipterocarp forest—KKU demonstrates one of the highest sequestration capacities (~18,000 tCO_2e/year) among Thai universities.

3.5.1 Design factors and strategic variables applied to KKU

The application of the design factor framework to Khon Kaen University (KKU) reveals how its operational profile influences the prioritization of interventions, as shown in Figure 4. In the domain of Built Environment and Energy, the high Energy Use Intensity (EUI) necessitates large-scale building retrofits, photovoltaic (PV) deployment, and energy storage solutions, with monitoring based on MRV indicators expressed as $kgCO_2e/m^2$·year. Within Mobility and Access, the predominance of private vehicles underscores the importance of electric shuttle systems (KKU Smart Transit) and bike-sharing programs, assessed in tCO_2e/FTE·year. Waste and Circularity strategies, such as composting and wastewater-to-biogas conversion, address Scope 3 waste streams, with performance tracked via diversion rates. Similarly, Water and Blue-Green Systems integrate wastewater-to-energy projects to enhance water efficiency while mitigating methane emissions. Land Use and Biodiversity measures emphasize the role of campus forests in carbon sequestration, expressed as tCO_2e per year. Finally, Governance and Digital Infrastructure call for integrating ISO 14064-1 standards with real-time MRV systems to ensure transparency and comparability across institutional and international benchmarks.

DF\Cluster	Large Comprehensive	Urban Specialized	Small Urban	Rural/Agricultural	Design Factor Name
DF01	1.200	0.920	0.618	0.700	Energy & Carbon Management
DF02	0.750	0.683	1.105	0.585	Sustainable Mobility
DF03	0.750	0.713	0.618	0.880	Water & Waste System
DF04	0.808	0.450	0.540	1.105	Green Infra & Ecosystem
DF05	0.750	0.840	0.920	0.690	Governance & Engagement
DF06	0.525	0.735	0.650	0.600	Education, Research & Innovation
	KKU				

Figure 4. Design factors' prioritization of interventions

3.5.2 Strategic initiatives and progress

KKU has formally committed to achieving carbon neutrality by 2040, positioning itself 25 years ahead of Thailand's national target. Strategic initiatives already implemented reflect both the university's high operational emissions and its significant potential for sequestration. These include:

1. Large-scale Renewable Deployment - 30 MW of solar farms and rooftop PV systems designed to reduce Scope 2 emissions.

2. Sustainable Mobility Transition - the launch of the KKU Smart Transit electric bus program, complemented by bicycle-sharing initiatives, directly reduces commuting-related emissions.

3. Circular Waste and Energy Projects - wastewater-to-biogas systems that capture methane and reduce Scope 1 emissions, alongside composting programs for organic waste.

4. Nature-Based Sequestration - continuous forest restoration initiatives that enhance long-term carbon sinks.

Each of these initiatives can be mapped directly to the Strategic Variables (SVs) outlined in the Strategic Variables and GHG Reduction (Table 5), where interventions are categorized under design factors such as energy, mobility, waste, and land use. This structured alignment illustrates how institutional commitments are operationalized into measurable actions, providing both accountability and a replicable model for other universities to follow.

Importantly, these initiatives are not carried out in isolation but are integrated into a KKU Net Zero Roadmap (Figure 5), which serves as a strategic pathway linking short-term actions with long-term decarbonization goals. By incorporating the SV-based framework into the roadmap, KKU ensures that each intervention aligns with measurable GHG reduction outcomes, financial viability, and effective governance structures. This roadmap approach provides clarity on timelines, milestones, and monitoring responsibilities, while also allowing for iterative adjustments in response to emerging technologies and policy developments. As a result, it turns strategic plans into a flexible operational blueprint, strengthening KKU's position as a national and regional leader in university-driven climate action.

Table 5. Strategic variable and GHG reduction

SV Code	SV Name	DF	Scope	SV Score	GHG Reduction	Horizon
SV-DF06-03	R&D on RE & CCUS	DF06	ALL	0.010	866.23	Long
SV-DF06-02	Living Lab Campus	DF06	ALL	0.012	1,082.78	Long
SV-DF06-04	Partnership with Industry/Gov.	DF06	ALL	0.017	1,517.06	Long
SV-DF03-04	Circular Procurement	DF03	S3	0.018	373.89	Long
SV-DF05-02	MRV (ISO 14064 + TGO CFO)	DF05	ALL	0.020	1,806.03	Long
SV-DF02-02	Modal Shift (Bike/Transit)	DF02	S3	0.031	626.93	Long
SV-DF06-01	Curriculum on Sustainability	DF06	ALL	0.032	2,882.42	Long
SV-DF02-03	Policy Less Personal Car	DF02	S3	0.033	685.70	Long
SV-DF02-01	EV Campus & Charging Infra	DF02	S1	0.035	820.26	Long
SV-DF05-03	Stakeholder Engagement	DF05	ALL	0.036	3,250.85	Long
SV-DF05-01	Net Zero Policy & Roadmap	DF05	ALL	0.038	3,431.46	Long
SV-DF02-04	Business Travel Management	DF02	S3	0.039	789.33	Long
SV-DF03-01	Smart Water Management	DF03	S1	0.052	1,201.71	Long
SV-DF04-03	Biodiversity Corridors	DF04	ALL	0.054	4,931.22	Long
SV-DF05-04	Carbon Credit / T-VER	DF05	ALL	0.060	5,418.09	Long
SV-DF03-03	Zero Waste to Landfill	DF03	S3	0.067	1,377.18	Long
SV-DF01-04	Carbon Accounting & Budget	DF01	S1	0.071	1,652.39	Long
SV-DF03-02	Wastewater to Biogas	DF03	S1	0.120	2,772.53	Medium
SV-DF01-03	Smart Grid & Demand Response	DF01	S2	0.124	5,852.70	Medium
SV-DF04-04	Nature-based Solutions (NbS)	DF04	ALL	0.141	12,821.16	Medium
SV-DF04-01	Green Space Expansion	DF04	ALL	0.184	16,766.14	Medium
SV-DF01-02	Building Energy Efficiency	DF01	S2	0.191	9,029.88	Medium
SV-DF04-02	Carbon Sequestration Forestry	DF04	ALL	0.230	20,957.67	Medium
SV-DF01-01	Renewable Energy Integration	DF01	S2	0.245	11,618.60	Medium

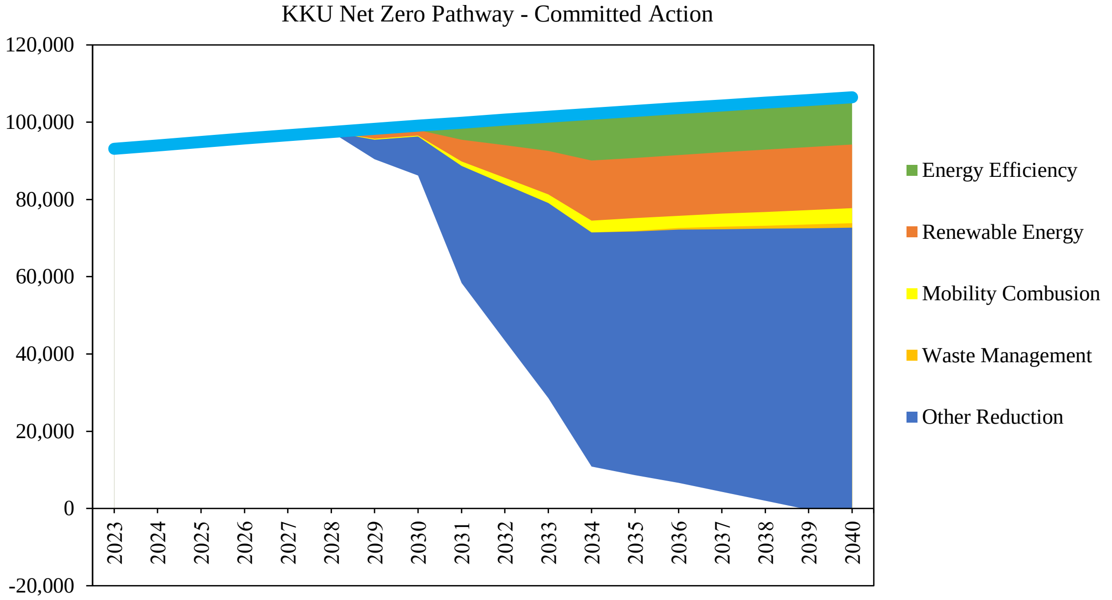

Figure 5. KKU net zero pathway

3.5.3 Challenges and comparative insights

Despite these achievements, several limitations persist. First, the high EUI of the climate-sensitive building stock underscores the urgent need for systematic retrofitting and the implementation of smart energy management systems. Second, Scope 3 accounting remains incomplete, particularly for commuting, procurement, and food services, thereby limiting the accuracy of KKU's carbon footprint. Third, the absence of a unified digital MRV platform limits transparency and comparability of emissions data. Finally, a lack of financial instruments, such as internal carbon pricing or dedicated green investment funds, constrains the university's capacity to mobilize resources toward its net- zero roadmap.

3.6 Synthesized tool and application to KKU

Building on the synthesis process, the outcome was a University Net Zero Planning Tool designed to integrate data, design factors, and strategic planning. The tool consists of four modules:

(1) Inventory Module: consolidates Scope 1-3 emissions using standardized factors and institutional data.

(2) Clustering Engine: groups universities based on energy intensity, sequestration potential, and operational scale. The indicators applied include Energy Use Intensity (kWh/m²/year), Emission Intensity (tCO_2e/student/year), Sequestration Index (tCO_2e/hectare/year), and Commuting Emission Share (% of total emissions). This multidimensional clustering approach is consistent with international benchmarking methods (Helmers et al., 2021; Lin et al., 2024; Paredes-Canencio et al., 2024).

(3) Design Factor Matrix: links each emission source to measurable indicators and potential interventions. The matrix covers six domains: Built & Energy (e.g., retrofit index, renewable fraction), Mobility (modal shift index, EV adoption rate), Waste (recycling ratio, waste-to-energy factor), Water (water reuse rate, treatment efficiency), Land Use (green space per capita, sequestration factor), and Governance (policy integration index, MRV maturity score). Similar frameworks have been outlined by Wang et al. (2023) and Aghamolaei and Fallahpour (2023).

(4) Roadmap Generator: produces scenario-based pathways aligned with national targets and institutional capacity. The generator employs back-casting principles—starting from a 2040/2050 net-zero target and mapping backward to identify milestones, technology adoption rates, and governance reforms. It incorporates sensitivity analysis for financial feasibility (Li and Jia, 2022) and city-scale transition synergies (Islam et al., 2023).

Applied to KKU, the tool quantified emissions, identified Scope 3 commuting impacts, and estimated sequestration from campus forests. It created a strategic roadmap focusing on solar expansion, EV transit, wastewater-to-biogas, and governance reforms. This roadmap was validated through expert consultations and institutional strategy documents, ensuring both feasibility and alignment with Thailand's net-zero 2065 goals.

3.7 Strengthened discussion with recent studies

Recent works (Wang et al., 2023; Paredes-Canencio et al., 2024; Islam et al., 2023; Aghamolaei and Fallahpour, 2023; Zheng et al., 2021; Lin et al., 2024; Li and Jia, 2022) expand the understanding of carbon neutrality in universities and strengthen the framework presented here. They highlight integrated approaches, ongoing weaknesses in Scope 3 management, the need for MRV standardization, financial viability, and city-wide synergies. KKU's case aligns with these insights, confirming the global relevance of its strategies.

4. CONCLUSION

This study introduces and validates a University Net-Zero Planning Tool, a strategic framework designed to guide Thai universities toward achieving carbon neutrality by employing systematic review, clustering analysis, and the synthesis of design factors. The results confirm that Scope 3 emissions, especially those linked to commuting and procurement; are the most prominent, while sequestration potential varies across institution types. The four driver indices (RHCI, UMPI, LGCI, IGRI) offer a solid basis for classifying universities into distinct clusters, facilitating more customized decarbonization strategies.

Applied to KKU, the tool highlights both challenges and opportunities: high operational emissions but also strong sequestration potential. The framework provides a replicable model for Thai universities and contributes globally to campus-based climate governance.

The analysis reveals: (1) KKU and other flagship universities have high EUI driven by energy-intensive facilities, (2) Scope 3 sources (commuting, procurement) constitute a substantial share of campus emissions (see Figure 5), and (3) effective decarbonization requires integrated measures and an MRV system.

KKU's EUI (~270 kWh/m²) and emissions intensity are in the top quartile of the Thai sample and comparable to those of large international campuses. Sensitivity tests (varying the grid factor and commuting assumptions) show that KKU's core findings remain stable.

Policy implications are threefold. First, national and institutional climate policies must go beyond energy efficiency to include sustainable mobility, procurement, and campus-wide behavioral change. Second, developing a standardized digital MRV system is essential for transparency, comparability, and alignment with Thailand's national climate commitments. Third, tailored incentives and support mechanisms are necessary, recognizing that urban flagships, regional comprehensives, suburban universities, and agricultural campuses each face distinct carbon challenges and opportunities.

In conclusion, universities can serve as 'living laboratories' for low-carbon transitions (Evans et al., 2015; Yusoff et al., 2021), and the proposed framework offers policymakers a replicable tool to accelerate progress toward Thailand's 2050 carbon neutrality and 2065 net-zero targets. The framework is transferable to other developing-country contexts if three conditions are addressed: (i) a minimum viable dataset (Scope 1-2 plus core activity indicators), (ii) a staged plan to expand Scope 3 categories as data capacity improves, and (iii) a governance entity responsible for MRV integration and target accountability. We therefore propose a four-level adoption pathway, allowing institutions with limited data to start with robust Scope 1-2 benchmarking before progressing to full Scope 1-3 MRV and verification.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no competing interests.

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