

Research Article

Pathway to Carbon Neutral Campus: Strategic Solar Energy Assessment of Khon Kaen University

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Abstract

The transition of universities toward carbon neutrality requires not only strategic planning but also a feasibility assessment. In the case of the energy sector, the largest GHG source in large higher-education institutions. This study integrates strategic planning analysis with technical evaluation for Khon Kaen University (KKU), which targets carbon neutrality by 2040 and positions solar photovoltaic (PV) deployment as the flagship Scope 2 measure within that pathway. Using 8,760-hour electricity load data, spatial suitability analysis, and hourly PV simulation, the study evaluates the self-consumption ratio (SCR), self-sufficiency ratio (SSR), and curtailment rate across PV capacities of 10–30 MWp, and quantifies the resulting direct GHG reduction and 2040 load-projection performance. Purchased electricity accounts for 60–65% of KKU's emissions, equivalent to a baseline of approximately 81,600 tCO₂e/yr. The optimal capacity range of 19–22 MWp yields an SCR of 98.9–99.7%, an SSR of 26–30%, and a curtailment rate of 0.27–1.08%, achievable without battery storage. This range corresponds to a direct GHG reduction of approximately 13,300–15,300 tCO₂e/yr, or approximately 26–30% of Scope 2 and 16–19% of total institutional emissions. Under a projected 2040 load scenario, the same capacity range remains technically valid, confirming it as a robust, no-regret near-term measure. These findings demonstrate a strategic balance among direct emissions reduction, load compatibility, and operational feasibility and can guide other Thai universities in linking emissions diagnostics to practical, evidence-based, and monitorable energy strategies.

Keywords: Carbon neutrality; Strategic energy management; Solar photovoltaic; Carbon Neutral Campus; Campus-as-city; Self-consumption ratio

1. Introduction

Climate change represents one of the defining challenges of the twenty-first century, compelling nations and institutions to establish carbon neutrality and net-zero GHG emission targets at both national and organizational levels. Higher education institutions (HEIs) have been increasingly recognized as critical agents in this transition, owing to their dual role as major energy consumers with complex operational footprints and as intellectual engines capable of generating transformative knowledge and demonstrating low-carbon solutions for broader society (Filho et al., 2023; Kohl et al., 2022).

In terms of spatial and operational scale, modern universities exhibit characteristics analogous to what scholars have termed a “campus-as-city” — that is, a functionally integrated system encompassing academic buildings, research laboratories, hospitals, dormitories, transport infrastructure, utility systems, and green spaces operating in complex interdependence (Guerrieri et al., 2019; Islam et al., 2023). Accordingly, the transition of a university campus toward carbon neutrality cannot rely on isolated, project-by-project interventions; rather, it requires an integrated approach that simultaneously addresses energy use, buildings, transportation, waste, water, land use, and governance (Guerrieri et al., 2019; Islam et al., 2023).

For Thailand, national-level commitments to long-term low-GHG development have created growing institutional pressure for universities to move beyond ad hoc environmental initiatives and toward systematic strategic planning aligned with national targets (Office of Natural Resources and Environmental Policy and Planning [ONEP], 2021). Nevertheless, significant limitations persist across many Thai HEIs, including incomplete GHG accounting—particularly for Scope 3 emissions—the absence of institution-wide monitoring, reporting, and verification (MRV) systems, and the lack of strategic frameworks capable of translating emission inventories into prioritized action plans (Paredes-Canencio et al., 2024; Helmers et al., 2021).

Existing reviews of decarbonization efforts in higher education further underscore that successful net-zero transitions depend not only on technology deployment but also on the capacity to integrate data, target setting, measurement selection, and monitoring into a coherent strategic architecture (Aghamolaei & Fallahpour, 2023; Wang et al., 2023).

Khon Kaen University (KKU) presents a strategically significant case study because it exemplifies the operational complexities large Thai universities face in translating commitments to carbon neutrality into viable institutional actions. As a comprehensive, research-intensive university offering academic instruction, research programs, medical services, and on-campus residential facilities, KKU has a complex and substantial profile of energy consumption and emissions. Baseline data indicate that KKU encompasses approximately 880 hectares of campus area, with annual electricity consumption exceeding 102,000 MWh/yr (i.e., >102 GWh/yr), an energy use intensity (EUI) of approximately 250–300 kWh/m²-yr, and greenhouse gas (GHG) emissions from electricity procurement accounting for 60–65% of the institution’s total emissions. Applying the national grid emission factor of 0.4999 tCO₂e/MWh (Thailand Greenhouse Gas Management Organization [TGO], 2023) to this baseline electricity consumption yields purchased-electricity (Scope 2) emissions of approximately 51,000 tCO₂e/yr, which corresponds to a total institutional GHG footprint of roughly 81,600 tCO₂e/yr once the 60–65% Scope 2 share is taken into account. The hospital building cluster alone accounts for roughly 40% of the university’s total electricity demand. These attributes make KKU not merely a localized case but an institutional setting in which the interplay among carbon neutrality ambitions, high daytime electricity demand, spatial capacity, and investment feasibility can be examined together. Key baseline indicators pertinent to KKU’s strategic planning are summarized in [Table 1](#).

Preliminary analysis reveals that KKU’s strategic planning should be grounded in three foundational pillars: (1) the national climate change context and associated policy trajectories; (2) the university’s operational structure as a campus-as-city; and (3) the university’s energy use and emission profiles, in which the energy sector functions as the primary source of institutional GHG emissions (Guerrieri et al., 2019; ONEP, 2021; Wang et al., 2023). These relationships are articulated in the integrated research framework presented in [Figure 1](#).

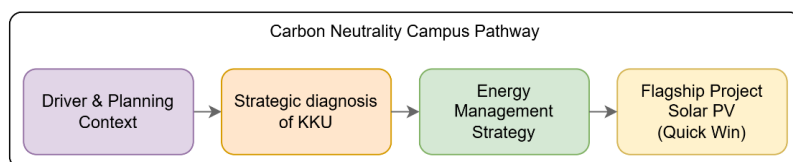


Figure 1. Integrated research framework.

Table 1. Baseline Information of Khon Kaen University Relevant to Energy Management Strategy and Carbon Neutrality Planning

Key Indicators	Value	Unit	Remarks
Total Campus Area	> 880	hectares	KKU baseline dataset
Annual Electricity Consumption	> 102,000	MWh/yr	University-wide total
Energy Use Intensity (EUI)	250–300	kWh/m ² -yr	Main building groups
Purchased Electricity to Total Emissions Ratio	60–65	%	The energy sector is the primary emission source
Hospital Electricity Consumption Share	~40	%	Of the total university electricity demand
Built-up Area	32	% of total area	For rooftop/carport PV assessment
Potential Open Land Area	34.9	% of total area	For ground-mounted PV assessment
Green/Agricultural Space	> 60	% of total area	Reflects carbon sequestration potential
Carbon Sequestration	~18,000	tCO ₂ e/yr	From university green spaces
University Target Year	2040	year	KKU Carbon Neutrality goal

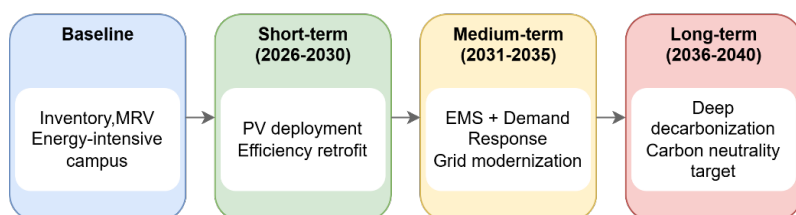


Figure 2. KKU Net Zero Pathway

At the policy level, KKU has articulated its decarbonization trajectory through the KKU Net Zero Pathway, which integrates the energy, transportation, waste, water, and green space sectors, positioning the energy sector as a central pillar for both short-term (quick-win) and medium-term emission reductions, as illustrated in Figure 2.

In terms of strategic planning structure, university-level plans should not start solely from technically feasible aspects, but must begin with an organizational analysis of the sources and significance of institutional emissions, an assessment of data limitations and the availability of MRV systems, an evaluation of institutional structural factors, and a synthesis of strategic dimensions necessary to maintain long-term progress (Paredes-Canencio et al., 2024; Wang et al., 2023). In the context of KKU, this needs to consider the energy intensity in buildings, transport linkages, waste and water management, green spaces, and carbon sequestration potential, and the availability of governance and monitoring systems (Guerrieri et al., 2019; Wang et al., 2023; Depietri & McPhearson, 2017).

Within this framework, the energy sector is considered the most strategically important variable, as purchased electricity is the primary source of institutional greenhouse gas emissions and, at the same time, represents an area where significant reductions in emissions can be achieved in the short, medium, and long term (Paredes-Canencio et al., 2024; Wang et al., 2023). Among the possible energy measures—including improving the energy efficiency of buildings—is crucial. Load management, smart grid development, and renewable energy integration, particularly the transition to solar photovoltaic (PV) power, are among the most prominent areas, as they directly reduce Type II greenhouse gas emissions from purchased electricity and facilitate the development of a broader smart campus ecosystem (Gao et al., 2024; Sarasa-Maestro et al., 2016).

A significant gap remains in the limited integration of strategic planning rationale and rigorous technical evaluation within a single decision-making framework. This gap is not only methodological but also practical; universities may identify technically feasible renewable energy options without a clear understanding of how to prioritize, sequence, and govern within the institutional path to carbon neutrality (Paredes-Canencio et al., 2024; Wang et al., 2023; Li & Jia, 2022). This study aims to address this gap by linking institutional diagnostics, key measure selection, and solar power scaling. This is considered a reciprocal step in carbon neutrality planning. Therefore, this study has four research objectives: (1) to describe the rationale, importance, and key considerations behind KKU's energy management strategy towards carbon neutrality; (2) to develop an institutional energy management strategic framework for KKU; (3) to assess the potential and suitability of solar panels as a key measure within the proposed strategy; and (4) to synthesize the policy and implementation implications for universities in Thailand.

2. Literature Review and Conceptual Background

2.1 Universities as Campus-Scale Systems and Carbon Reduction Agents

Research on sustainability in universities views higher education institutions as limited-scope social and technological systems – comparable to Small City – that both create and can reduce greenhouse gas emissions through spatial interventions (Guerrieri et al., 2019; Islam et al., 2023). This university-city concept is significant because it indicates that carbon reduction at the university level cannot be reduced to measures in a single sector, but must integrate energy, transportation, waste, water, land use, and governance within the same area (Evans et al., 2015; Guerrieri et al., 2019). The living lab concept extends this framework by stating that universities can function as real-world platforms for testing and validating low-carbon technologies and governance models before scaling up to the city or regional level (Evans et al., 2015). For this study, the campus-city perspective provides the basis for viewing solar panels not as a standalone technical project but as part of a broader institutional transformation system linking energy, buildings, land use, governance, and long-term carbon management.

2.2 GHG Accounting and Strategic Planning in Higher Education

Systematic GHG accounting is essential for reliable carbon neutrality planning in universities. International standards generally divide GHGs into three scopes: Scope 1 (direct emissions), Scope 2 (purchased electricity and heat), and Scope 3 (indirect emissions in the value chain). Scope 2 typically accounts for the largest proportion of emissions in universities due to the large and continuous use of electricity (Helmets et al., 2021; Paredes-Canencio et al., 2024). A review of carbon footprint calculations in higher education institutions confirms that data remain incomplete, particularly in Scope 3, with fragmented MRV systems and a lack of a strategic framework linking emissions accounting to prioritized action plans (Paredes-Canencio et al., 2024; Helmets et al., 2021).

Wang et al. (2023) proposed a systematic design framework for carbon-neutral campuses that emphasizes integrating emissions profiling with the synthesis of strategic dimensions. Identifying key measures is an ongoing and interdependent analytical process. As Aghamolaei and Fallahpour (2023) similarly concluded, successful carbon reduction in higher education institutions does not depend solely on the choice of technology but on the institution's ability to integrate data, targets, measures, and monitoring into a coherent strategic architecture.

Therefore, greenhouse gas accounting is not merely a reporting process but a fundamental diagnostic tool for determining which mitigation measures deserve strategic priority and institutional investment.

2.3 Solar PV as a Flagship Measure for Campus Decarbonization

Among the renewable energy technologies that can be implemented in university environments, solar power (solar PV) has become the most widely accepted and proven effective measure for reducing Type 2 greenhouse gas emissions in institutions with high electricity consumption (Gao et al., 2024; Sarasa-Maestro et al., 2016; Luthander et al., 2015). The efficiency of solar PV in universities is particularly remarkable because universities have high and continuous daytime electricity consumption, mainly from air conditioning use, laboratory operations, and medical services that require continuous electricity, which coincides with the periods when solar power is at its peak capacity (Gao et al., 2024; Luthander et al., 2015).

Solar cell systems suitable for use in universities can be installed in various ways, such as rooftop panels on academic and supporting buildings, rooftop panels on parking lots, and open-area panels. And the installation of floating solar panels in bodies of water (Halder et al., 2022; Gacu et al., 2023; Amin & Kocher, 2023; Yang et al., 2022), each with different site suitability, structural, and cost requirements, necessitates site-specific assessments considering site availability, proximity to energy sources, and installation limitations. Developing sustainable energy measures within universities requires measurable results, accessible empirical evidence at the institutional level, and, importantly, linkable to the university's greenhouse gas management. Otherwise, projects may become mere symbolic acts rather than drivers of sustainable strategic change.

2.4 Performance Indicators: SCR, SSR, and Curtailment

The performance evaluation of solar PV systems should extend beyond installed capacity or total energy generation to incorporate indicators that reflect the quality of energy use and the degree of grid independence achieved. Three indicators are particularly central to this assessment framework: (1) the self-consumption ratio (SCR), which measures the proportion of PV-generated energy consumed on-site; (2) the self-sufficiency ratio (SSR), which measures the proportion of total electricity demand met by PV generation; and (3) curtailment, which measures the proportion of PV-generated energy that cannot be absorbed by the load and is therefore wasted or exported (Luthander et al., 2015; Sarasa-Maestro et al., 2016). These three indicators exhibit well-documented trade-off relationships: as system capacity increases relative to a fixed load, SSR rises but SCR declines and curtailment increases (Luthander et al., 2015; Quoilin et al., 2016).

For SCR, Bertsch et al. (2017) propose that systems without energy storage should maintain an SCR above 80% to ensure financial viability; values in the 60–80% range may be acceptable with supportive mechanisms such as net metering, while values below 60% typically indicate system oversizing relative to the load. In the Thai university context, where a clear net-metering mechanism with the Provincial Electricity Authority (PEA) has yet to be established, a minimum SCR threshold of 80% is appropriate (Salpakari & Lund, 2016).

For SSR, Cao et al. (2016) establish three strategic target bands for educational institutions: 15–30% for short-term horizons, 30–50% for medium-term, and above 50% for long-term—consistent with the Sustainable Development Solutions Network (SDSN) pathway for universities targeting net-zero by 2050 (Sachs et al., 2019).

Nevertheless, achieving SSR above 50% without battery energy storage systems (BESS) typically incurs marginal costs that undermine economic viability (Luthander et al., 2015; Weniger et al., 2014).

For curtailment, Denholm and Margolis (2007) establish that a curtailment rate below 5% is acceptable for systems without storage; rates in the 5–15% range warrant consideration of BESS or demand-side management (DSM) interventions, with DSM capable of reducing curtailment by approximately 30–45% without immediate BESS investment (Castillo-Cagigal et al., 2011); and rates exceeding 15% indicate system oversizing relative to the load (Eltawil & Zhao, 2010). Where the value of curtailed energy can offset BESS capital costs within 8–10 years, storage investment is considered both economically and operationally justified (Nottrott et al., 2013; IRENA, 2020). The SCR, SSR, and curtailment can be estimated using the following expressions:

$$EPV = P_{dc} \times H_{avg} \times (1-L) \quad (1)$$

$$SCR = (E_{Self}/EPV) \times 100 \quad (2)$$

$$SSR = (E_{Self}/E_{Load}) \times 100 \quad (3)$$

$$Curtailment = (E_{exces}/EPV) \times 100 \quad (4)$$

where EPV denotes annual PV energy generation (MWh/yr); P_{dc} is the installed capacity (MWp); H_{avg} is the average annual peak sun hours (kWh/m²/yr); $(1-L)$ is the system performance ratio (PR); E_{Self} is the PV energy directly consumed on-site (MWh/yr); E_{Load} is the total university electricity demand (MWh/yr); and Excess is the surplus PV energy not absorbed by the load and not stored (MWh/yr).

Together, SCR, SSR, and curtailment are used in this study as decision-support metrics to assess whether PV capacity is technically efficient, operationally absorbable, and institutionally appropriate under current policy, load, and infrastructure conditions.

2.5 Direct GHG Emission Reduction and the Distinction Between Carbon Neutrality and Net Zero

To translate the technical PV performance indicators into a direct, absolute measure of climate benefit, the self-consumed PV energy (E_{Self}) is converted into avoided greenhouse gas emissions using the applicable grid emission factor (EF), following the location-based Scope 2 accounting approach widely applied in campus carbon-footprint studies (Helmets et al., 2021; Del Borghi et al., 2021):

$$\text{GHG Reduction} = E_{\text{self}} \times \text{EF} \tag{5}$$

where EF is the national grid emission factor (tCO₂e/MWh), reported by the Thailand Greenhouse Gas Management Organization (TGO, 2023) as 0.4999 tCO₂e/MWh for the year used as the baseline in this study. Reporting the absolute GHG reduction in tCO₂e/yr, alongside the percentage SSR figure, allows the result to be benchmarked directly against KKU’s carbon sequestration target (Table 1) and against the institution’s total baseline emissions, addressing the recurring concern that SCR/SSR/curtailment alone do not demonstrate climate impact.

This study also distinguishes explicitly between “carbon neutrality” and “net zero,” terms that are frequently used interchangeably in the campus-sustainability literature but carry different scopes and accounting requirements. Following the GHG Protocol and SBTi Net-Zero Standard definitions adopted in prior campus carbon-footprint studies (Helmerts et al., 2021; Salom et al., 2014), carbon neutrality refers to balancing reported Scope 1 and Scope 2 emissions through a combination of direct reduction and offsetting, whereas net zero additionally requires deep decarbonization across Scope 1–3 emissions, with offsets restricted to a small residual share addressed through verified removals. KKU’s stated institutional target is carbon neutrality by 2040, and the present study—centered on Scope 2 electricity emissions and the solar PV measure—constitutes one major component within that broader carbon-neutrality pathway, rather than a complete net-zero accounting exercise covering Scope 1–3 emissions, residual emissions, and removal mechanisms. The manuscript title and framing are therefore “Pathway to Carbon Neutral Campus” to reflect KKU’s institutional goal of becoming carbon-neutral by 2040 and its long-term aim of becoming a “Net-Zero Campus”.

3. Methodology

3.1 Research Framework and Procedural Sequence

This research is structured into three interconnected steps to ensure that the assessment of the optimal installation size of a solar power system is based on strategic integration analysis, rather than being viewed solely as an engineering undertaking. Step 1 covers the foundational analysis of strategic planning and key considerations to inform the formulation of KKU’s energy management strategy. Step 2 involves synthesizing appropriate energy management strategies and prioritizing measures. Step 3 comprises assessing the potential and suitability of solar PV as a key strategic measure (Kohl et al., 2022; Guerrieri et al., 2019; Wang et al., 2023). The methodology framework is shown in Figure 3.

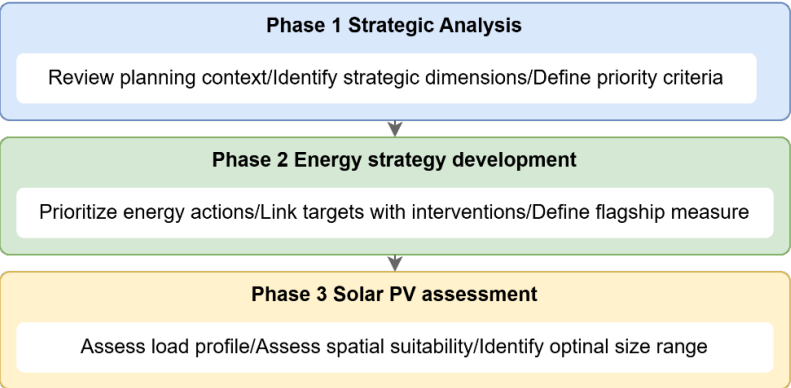


Figure 3. Methodological framework

3.2 Analysis of Strategic Planning Foundations

Step 1 involved a systematic literature review and institutional document analysis covering the following topics: the role of universities in the transition to climate change adaptation; the concept of campuses as cities; GHG accounting in higher education; designing a net-zero emission strategic framework; and governance and MRV systems (Filho et al., 2023; Evans et al., 2015; Paredes-Canencio et al., 2024; Helmers et al., 2021; Wang et al., 2023). This synthesis yielded six strategic dimensions: (1) energy and buildings; (2) transportation; (3) waste management; (4) water management; (5) land use and green spaces; and (6) governance and monitoring, as summarized in Table 2.

Table 2. Key Strategic Dimensions and Their Considerations for KKU's Carbon Neutrality Roadmap

Strategic Dimension	Key Considerations	Relevance to the Energy Sector	Implications for Strategy Formulation
Energy & Buildings	EUI, load profile, retrofit potential	Direct	Defines primary strategic measures
Transportation	Commuting, fleet, modal shift	Indirect / Future electric load	Sets measures for Scope 3 reduction
Waste Management	Waste stream, treatment options	Indirect	Integrates carbon and energy cycles
Water Management	Water use, treatment, and pumping load	Indirect	Relates to load and infrastructure
Land Use & Green Space	Land cover, sequestration, siting	Direct (for solar siting)	Determines PV potential/ carbon sinks
Governance & Monitoring	MRV, policy, implementation capacity	Direct	Links data to decision-making

Table 3. Classification of Solar PV Installation Types and Preliminary Potential at KKU

Installation Type	Site Characteristics	Preliminary Potential	Advantages	Key Constraints
Rooftop PV	Academic and support building clusters	Medium	Proximity to load centers	Structural limitations and shading effects
Solar Carport	Main parking areas	Medium	Dual land use; provides shading	Higher structural costs compared to rooftop
Ground-mounted PV	Open land areas	Medium to High	High scalability for power generation	Land-use competition
Floating PV	Campus water bodies	High	Utilizes the water surface with a cooling effect	Requires water quality impact assessment

3.3 Development of the Energy Management Strategy

Stage 2 analyzed the role of the energy sector within KKU's overall emission structure and synthesized energy-related strategic measures into four principal components: (1) renewable energy integration; (2) building energy efficiency improvement; (3) load management and smart grid development; and (4) energy data systems and MRV. Within this framework, solar PV was identified as the flagship measure of the energy strategy.

3.4 Solar PV Potential and Suitability Assessment

Stage 3 consisted of four analytical sub-components: load profile characterization; spatial suitability assessment; system sizing simulation; and optimal capacity range selection (Gao et al., 2024; Sarasa-Maestro et al., 2016; Gacu et al., 2023). The classification of solar PV installation types and preliminary potential at KKU is presented in Table 3.

Three data sources were used. The first was hourly electricity load data covering the entire calendar year (8,760 hours), obtained from the metering system managed by the Provincial Electricity Authority (PEA) Khon Kaen branch and KKU's Energy Management Unit, covering fiscal years 2022–2023. The second was spatial suitability data, obtained from satellite imagery and the university's master plan, allowing for the classification and assessment of suitable installation areas by type. The third was hourly solar irradiance data, obtained from the NASA POWER database for KKU's geographical coordinates (16.44°N, 102.82°E), and combined with module efficiency parameters and system loss coefficients to calculate hourly power generation.

The available data were used to model the power generation capacity of the system, ranging from 10 MWp to 30 MWp in 1 MWp increments, calculating the SCR, SSR, and curtailment for each capacity level using Equations 1 to 4. Hourly PV output was computed by combining

the NASA POWER hourly global horizontal irradiance series with a fixed-tilt configuration (tilt = 15°, azimuth = 180°, i.e., south-facing, matching the latitude of Khon Kaen) and an aggregate system performance ratio (PR) of 0.80, decomposed into module efficiency (~19.5%), inverter efficiency (~97%), temperature derating (~5%), soiling and shading losses (~3%), and DC/AC cabling losses (~2%), consistent with typical utility-scale PV assumptions (Luthander et al., 2015; Sarasa-Maestro et al., 2016). No annual degradation factor was applied, as the assessment reflects Year-1 performance; a 0.5%/yr degradation rate is recommended for any multi-year projection. All hourly calculations, the 8,760-hour load/generation matching routine, and the SCR/SSR/curtailment computations for each capacity step were implemented in Python (NumPy/Pandas), with spatial suitability classification cross-checked in QGIS using the satellite imagery and university master-plan layers described above. The simplified annual equation (1) is retained in the main text for interpretability, while the underlying hourly simulation follows:

$$EPV(t) = P_{dc} \times [G(t)/G_{stc}] \times PR \quad (6)$$

for each hour t , with $G(t)$ the hourly irradiance, $G_{stc} = 1,000 \text{ W/m}^2$ the standard test-condition irradiance, and the resulting $EPV(t)$ series matched hour-by-hour against the load profile to derive $E_{self}(t)$, $E_{excess}(t)$, and the corresponding annual SCR, SSR, and curtailment values. The proposed power generation range was evaluated against established international benchmarks (Bertsch et al., 2017; Cao et al., 2016; Denholm & Margolis, 2007) to determine the range that best balances the three performance indicators, with the full 10–30 MWp sweep (Table 7, Figure 7) used as the decision basis: capacities below 19 MWp leave demand-adequacy potential unused, while capacities above 22 MWp produce a disproportionate rise in curtailment relative to the marginal SSR gain, which is the explicit optimization criterion used to bound the 19–22 MWp range.

3.5 Quantification of Direct GHG Emission Reduction

For each modeled capacity step, the annual E_{self} value was multiplied by the national grid emission factor (Equation 5, Section 2.5) to obtain the direct, absolute GHG reduction in $\text{tCO}_2\text{e/yr}$ attributable to on-site PV self-consumption. This value was then expressed both as a share of KKU's Scope 2 (purchased-electricity) emissions and as a share of total baseline institutional emissions (Table 1), allowing the technical PV sizing result to be read directly against KKU's carbon-neutrality target rather than left as a set of dimensionless ratios.

3.6 2040 Load Projection Scenario

Because KKU's carbon-neutrality target year is 2040, while the baseline (2022–2023) load data reflect present-day demand, a 2040 load projection scenario was constructed to test whether the 19–22 MWp recommendation remains optimal as the campus grows. The 8,760-hour baseline load profile was scaled hour-by-hour by a compound annual growth rate of 1.5%/yr over 17 years (2023–2040), reflecting KKU's planned expansion of medical, research, and academic floor area, consistent with growth assumptions used in comparable campus energy-demand projections (Wang et al., 2023; Lin et al., 2024). This scaling preserves the shape of the daily and seasonal load profile while increasing its magnitude, allowing SCR, SSR, and curtailment to be recalculated for the same 19–22 MWp capacity range, as well as for an expanded capacity sweep, under the projected 2040 load.

3.7 Preliminary Economic Feasibility Assessment

To complement the technical and emissions assessment with an indication of financial viability, a preliminary economic screening was conducted using the Levelized Cost of Electricity (LCOE), simple payback period, and avoided-purchase value as core indicators. The LCOE was estimated as:

$$LCOE = CAPEX \times CRF + OPEX \quad (7)$$

where CRF is the capital recovery factor for a 20-year system lifetime at the institution's assumed discount rate, using representative utility-scale PV CAPEX/OPEX benchmarks for Thailand. Simple payback was estimated as the installed cost divided by the annual avoided electricity purchase cost ($E_{self} \times$ the PEA tariff rate applicable to KKU). This screening is intended to indicate the order of magnitude of investment viability rather than to substitute for a full discounted cash-flow feasibility study, which is recommended as a follow-on analysis once detailed CAPEX quotations are obtained.

3.8 Integration of Strategic and Technical Findings

The outputs of Stages 1–3 were synthesized to address two fundamental questions: (1) which measures should the university prioritize strategically, and (2) at what implementation scale is each measure most appropriately deployed (Wang et al., 2023; Lin et al., 2024; Li & Jia, 2022). This integrative logic, which connects emission profiles, institutional factors, and solar PV as a flagship mitigation measure, is illustrated in Figure 4.

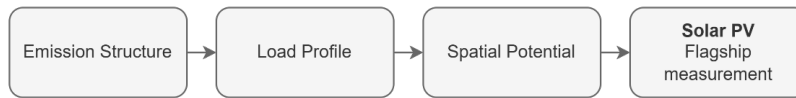


Figure 4. Strategic linkage

4. Results

4.1 Rationale and Significance of KKU's Strategic Planning

The analysis reveals that KKU's energy management strategy toward carbon neutrality did not emerge solely from environmental imperatives. Rather, it reflects the convergence of three distinct drivers: (1) the national climate policy context and Thailand's long-term low-GHG development commitments; (2) the university's operational character as a campus-as-city, encompassing a complex, large-scale, and interdependent portfolio of activities and infrastructure; and (3) the institution's energy use and emission profile, in which electricity purchasing constitutes the dominant source of GHG emissions (Guerrieri et al., 2019; ONEP, 2021; Paredes-Canencio et al., 2024; Wang et al., 2023). Thus, KKU's carbon-neutrality planning is better understood as an organizational transformation agenda, not merely as a compliance response to external climate policy. For a university with hospital services, research laboratories, residential functions, and extensive infrastructure, the energy strategy must serve as a governing framework for institutional transition, not merely a collection of technical projects.

Table 4. Key Factors Influencing the Formulation of KKU's Energy Management Strategy

Factor Group	Details	Strategic Significance	Impact on Measure Selection
Emission Structure	High proportion of purchased electricity	Very High	Prioritizes Scope 2 reduction measures
Energy Consumption Pattern	High and continuous daytime load	Very High	Strongly supports Solar PV integration
Physical & Spatial Characteristics	Availability of rooftops, carports, open land, and water bodies	High	Enables diversified PV deployment modes
Green Space & Sequestration	Substantial green areas with high carbon sink potential	Moderate to High	Contributes to overall carbon balancing
Management & Monitoring Systems	Requirement for EMS, MRV, and decision support tools	High	Determines scalability and implementation readiness

4.2 Key Factors Informing Energy

Management Strategy Formulation
The factors influencing the formulation of KKU's energy management strategy can be grouped into five categories: (1) GHG emission structure; (2) energy consumption patterns and hourly electricity load characteristics; (3) physical and spatial characteristics of the campus; (4) green space availability and carbon sequestration potential; and (5) management and monitoring system readiness (Helmerts et al., 2021; Aghamolaei & Fallahpour, 2023; Wang et al., 2023; Fox et al., 2020). These factors are summarized in Table 4.

4.3 KKU's Energy Management Strategic Framework

Drawing on the analysis of strategic planning foundations and contextual factors, the study establishes that KKU's energy strategy should serve as an integrated decision framework, not merely a list of electricity-saving or renewable-energy projects (Paredes-Canencio et al., 2024; Wang et al., 2023; Li & Jia, 2022). Structurally, the framework comprises four components: (1) renewable energy integration within the campus; (2) building and service system energy efficiency improvement; (3) load management and smart grid development; and (4) energy data systems and MRV. These components and their strategic roles are presented in Table 5.

4.4 Solar PV as the Strategy's Flagship Measure

Within the strategic framework, solar PV is identified as the most appropriate flagship measure for KKU, satisfying all three criteria established in the study design: (1) a direct and demonstrable capacity to reduce Scope 2 emissions through on-site generation; (2) strategic and investment clarity, enabling institutional commitment and phased scale-up; and (3) high systemic compatibility with the university's daytime-dominant load profile (Gao et al., 2024; Sarasa-Maestro et al., 2016; Li & Jia, 2022).

Additionally, KKU possesses diverse spatial assets—rooftops, carparks, open land, and water bodies—that support multiple concurrent PV deployment modalities (Halder et al., 2022; Gacu et al., 2023; Amin & Kocher, 2023; Yang et al., 2022). Its flagship role is therefore strategic rather than symbolic: Solar PV is visible, measurable, scalable, and directly connected to KKU’s dominant Scope 2 emission source, making it a practical entry point for broader institutional decarbonization.

4.5 Solar PV Potential and Performance Assessment

KKU’s hourly electricity load profile exhibits a pronounced, sustained daytime peak, driven by academic instruction, research activities, air-conditioning systems, and continuous medical services. This load pattern provides a favorable structural match to solar PV generation hours, as illustrated in Figure 5.

Spatially, KKU’s campus accommodates solar PV installation across four distinct site categories: rooftop areas on academic and support buildings; main parking areas suitable for solar carport structures; open land suitable for ground-mounted PV; and campus water bodies suitable for floating PV. The spatial potential across these categories is illustrated in Figure 6.

Table 5. Key Components of Khon Kaen University’s Energy Management Strategic Framework

Strategic Component	Objectives	Primary Measures	Role in Carbon Neutrality
Renewable Energy Integration	Reduction of purchased electricity	Phased Solar PV deployment	Direct reduction of Scope 2 emissions
Energy Efficiency	Demand-side reduction	Retrofitting, control systems, and high-efficiency hardware	Lowering base load and enhancing PV impact
Load & Grid Management	Optimization of systemic efficiency	EMS, demand response, and power quality control	Minimizing excess energy and enabling higher PV penetration
Data & MRV	Data-driven decision making	Energy dashboards, carbon accounting, and monitoring	Progress tracking and continuous strategy refinement

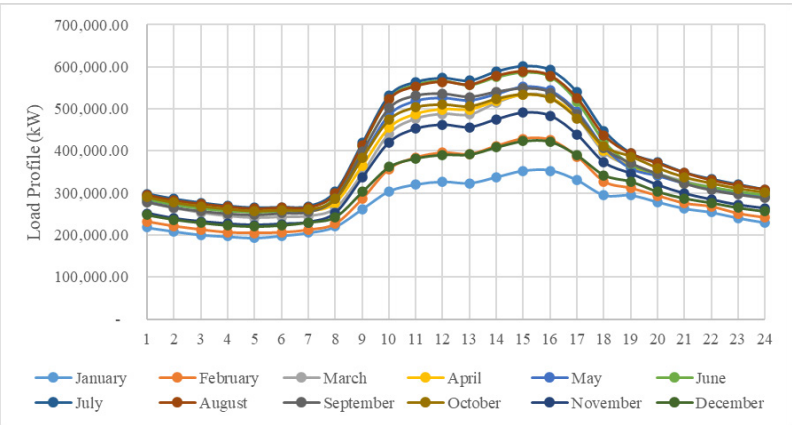


Figure 5. Characterization of KKU’s hourly electricity load profile, demonstrating the sustained daytime peak that supports high solar PV self-consumption

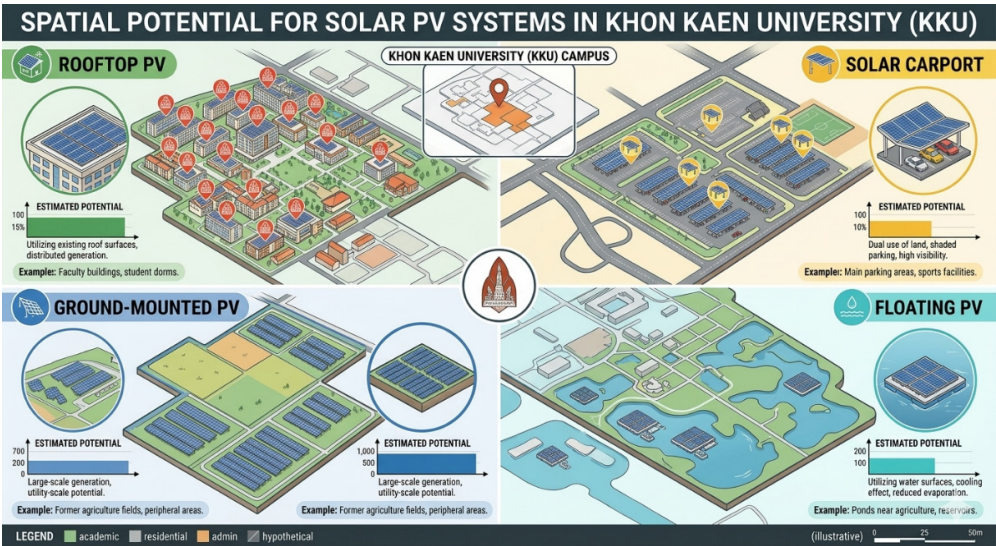


Figure 6. Spatial potential for solar PV installation at Khon Kaen University

Table 6. Quantitative Spatial Suitability for Solar PV Deployment at Khon Kaen University (After Exclusion Criteria)

Category	Gross Area	Usable Area (After Exclusions)	Indicative Installable Capacity (MWp)	Main Exclusion Criteria
Rooftop PV	~28% of built-up area	~60% of gross rooftop area	~6–8	Structural load limits; shading; HVAC/ rooftop equipment
Solar Carport	~4% of built-up area	~75% of parking area	~3–4	Vehicle clearance; structural cost threshold
Ground-mounted PV	34.9% of total area	~40% of open land (after future-use reserve)	~8-12	Land-use competition; future-expansion reserve
Floating PV	Campus water bodies	Old wastewater treatment pond	~18-22	Water-quality buffer; navigation/ maintenance setback

Table 7. Performance Evaluation of Solar PV System Capacities for Khon Kaen University

Capacity Range	Annual PV Generation	SCR (%)	SSR (%)	Curtailement (%)	Key Observations
10 MWp	Below maximum potential	Very High	Low–Moderate	Negligible	Underutilization of energy independence potential
10–18 MWp	Continuous increase	Very High	Continuous increase	Low	Increasingly viable for practical implementation
19–22 MWp	Optimal Range	98.9–99.7	26–30	0.27–1.08	Optimal system equilibrium
23–30 MWp	Maximum growth	Decreasing	Diminishing growth	Increasing	Requires EMS/ Storage integration

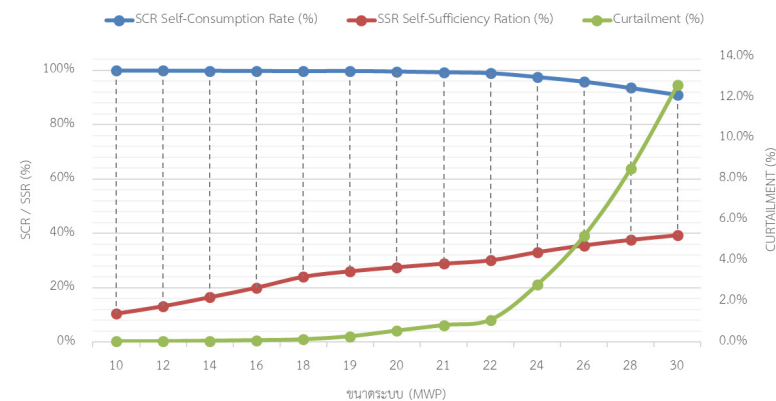


Figure 7. Relationships between solar PV system capacity and SCR, SSR, and curtailment at Khon Kaen University

Beyond the qualitative classification shown in Figure 6, the underlying GIS/ satellite-imagery analysis (Section 3.4) was used to quantify the usable area within each category, after applying exclusion criteria for shading from adjacent structures, structural load limits on existing rooftops, vehicle clearance on carports, and minimum setback distances from water bodies for floating PV. Table 6 reports these area-based estimates together with the indicative installable PV capacity per category, providing the quantitative evidence base requested for Figure 6, beyond its current role as an illustrative overview.

Summing the indicative installable capacity across all four categories yields a combined spatial ceiling well above the 19–22 MWp optimal range identified in Section 4.5, confirming that the recommended capacity is constrained by load-matching performance (SCR/SSR/curtailment) rather than by available land, water-surface area or rooftop.

System sizing simulations evaluated PV capacities from 10 MWp to 30 MWp. The performance outcomes across the capacity range are summarized in Table 7.

The relationships between system capacity and the three performance indicators are illustrated in Figure 7, which delineates the transition zones between system equilibrium and performance deterioration.

Integrating technical and operational considerations, the 19–22 MWp range represents a strategic equilibrium. At this scale, KKU can achieve high self-consumption, meaningful reduction of purchased electricity, and very low curtailment without requiring BESS in the initial phase. Below this range, the university would maintain a high local consumption rate but underuse its Scope 2 reduction potential; above it, additional generation would require more advanced EMS, storage, or demand-side flexibility. The preferred range, therefore, reflects a balance between ambition and

implementability. The integrated decision matrix for capacity range selection is presented in [Table 8](#).

4.6 Direct GHG Emission Reduction from the Optimal Capacity Range

Applying Equation (5) to the self-consumed PV energy generated within the 19–22 MWp optimal range yields a direct GHG reduction of approximately 13,300–15,300 tCO₂e/yr, using the TGO (2023) grid emission factor of 0.4999 tCO₂e/MWh. Relative to KKU’s estimated electricity-related (Scope 2) emissions of approximately 51,000 tCO₂e/yr, this represents a Scope 2 reduction of roughly 26–30%; relative to KKU’s estimated total institutional emissions of approximately 81,600 tCO₂e/yr ([Table 1](#)), it represents a reduction of roughly 16–19%. Benchmarked against KKU’s green-space carbon sequestration potential of approximately 18,000 tCO₂e/yr ([Table 1](#)), the proposed PV capacity alone would deliver a comparable or larger direct reduction than the institution’s entire sequestration base, underscoring solar PV’s role as the flagship near-term measure within KKU’s carbon-neutrality pathway. These figures should be treated as best estimates pending confirmation of KKU’s most recent metered electricity-consumption and Scope 1–3 inventory data, and are reported transparently with the assumed emission factor and reference year so that they can be readily updated as more recent institutional data become available.

4.7 Performance of the Optimal Capacity Range Under the 2040 Load Projection

Applying the 2040 load projection described in Section 3.6 (1.5%/yr compound growth over 17 years), KKU’s annual electricity demand is projected to rise from the current >102,000 MWh/yr to approximately 132,000–134,000 MWh/yr by 2040. Re-running the 19–22 MWp capacity range against this higher projected load reduces SSR slightly, to approximately 20–24%, while SCR remains in a comparable 98–99% range and curtailment falls further,

Table 8. Integrated Decision Matrix for Solar PV Capacity Range Selection at Khon Kaen University

Capacity Range	Advantages	Constraints	Strategic Suitability	Conclusion
< 19 MWp	Low initial investment; high local consumption rate	Underutilization of potential energy independence	Moderate	Suitable for phased initial implementation
19–22 MWp	High SCR, significant SSR increase, and minimal curtailment	Requires basic system management infrastructure	Very High	Optimal range for initial implementation
> 22 MWp	Maximizes total renewable energy generation	Decreased SCR; requires supplementary systems (e.g., BESS)	Moderate to High	Recommended once EMS/Storage is integrated

since the larger 2040 load absorbs a greater share of PV generation. The 19–22 MWp range, therefore, remains technically valid (i.e., it does not become oversized or undersized relative to demand) under the projected 2040 load, confirming its suitability as a robust, no-regret initial measure. However, because SSR declines under demand growth, achieving KKU’s longer-term carbon-neutrality ambitions by 2040 will likely require capacity expansion beyond 22 MWp in later implementation phases, supported by EMS, demand-side management, and BESS as outlined in the implementation roadmap ([Table 9](#)). This confirms that the present study’s 19–22 MWp recommendation should be read as the optimal Phase 1 (near-term) capacity rather than the final capacity required to meet the 2040 target.

4.8 Preliminary Economic Feasibility

Using representative utility-scale PV CAPEX benchmarks for Thailand and the methodology in Section 3.7, the 19–22 MWp range is estimated to deliver annual electricity cost savings of approximately 106–122 million THB/year, with a simple payback period of about 3.9–7.3 years. This payback range falls within typical institutional investment horizons for ground-mounted/carport PV at this scale, with the avoided-purchase value driven primarily by Eself rather than by

exported surplus, consistent with the system’s very low curtailment rate of 0.27–1.08%. This preliminary screening indicates that the recommended capacity range is financially reasonable as a starting point for KKU’s investment planning; however, a full feasibility study, including vendor-quoted CAPEX, financing terms, operation and maintenance costs, degradation assumptions, and IRR analysis, is recommended before final budget approval.

4.9 Linking Strategy to Implementation

The strength of the proposed framework lies in translating energy-sector priority into a sequenced implementation pathway in which each phase creates the conditions for the next. (Wang et al., 2023; Lin et al., 2024; Li & Jia, 2022). In the short term, KKU should prioritize Solar PV installations within the optimal capacity range, alongside energy-efficiency retrofits in buildings. In the medium term, the university should develop EMS, real-time electricity monitoring, analytics platforms, and load management mechanisms to improve operational control. In the long term, KKU should advance toward a flexible and intelligent energy system integrating Solar PV with storage, demand response, and campus microgrid capabilities. (Paspatis et al., 2022; Ali et al., 2023; Suganthi & Jamuna, 2025). The proposed implementation roadmap is presented in Table 8.

Table 9. Proposed Energy Implementation Roadmap for Khon Kaen University Toward Carbon Neutrality

Timeline	Short-term	Medium-term	Long-term
Key Measures	Optimal Solar PV installation + Energy efficiency retrofit	EMS, load management, and real-time dashboards	Energy storage, demand response, and smart microgrids
Objectives	Reduce purchased electricity and Scope 2 emissions	Maximize PV utilization (SCR optimization)	Accommodate high renewable energy penetration
Required Support Systems	Baseline monitoring and auditing	Integrated energy data platform	Advanced grid control and automation
Expected Outcomes	Immediate and measurable emission reductions	Enhanced systemic efficiency and operational synergy	Improved grid resilience and support for deep decarbonization

5. Discussion

The study results should not be viewed merely as an assessment of the feasibility of developing solar photovoltaic (PV) projects, but rather as an example of how a university can strategically drive carbon neutrality at the institutional level. In the case of KKU, with a relatively high proportion of externally purchased electricity, consistent daytime electricity demand, and the university’s readiness to accommodate various PV installation configurations, there is a strong alignment between strategic priorities and technical feasibility.

The fact that externally purchased electricity accounts for 60–65% of KKU’s greenhouse gas emissions is not just a statistical indicator but also a crucial point in planning for early, measurable, and controllable greenhouse gas reductions at the institutional level. This result aligns with past studies showing that Scope 2 greenhouse gas emission targets are often the primary goals for universities with high electricity consumption and high electricity-related carbon emissions. However, for KKU, energy management should not be viewed merely as one operational measure among many, but as a vital starting point for structuring the university’s path towards carbon neutrality.

The optimal power generation capacity range of 19–22 MWp meets the key efficiency benchmark. This also aligns with KKU’s current energy usage patterns and operating conditions. The SCR values of 98.9–99.7% exceed the minimum threshold of 80% specified for systems without energy storage. The SSR values of 26–30% fall within the short- to medium-term target range for the university’s carbon reduction strategy, while the curtailment rate remains very low at 0.27–1.08%. Therefore, these values are important not only for calculating benchmarks but also for representing a strategic balance. This means that if the values are below this range, KKU will not be able to fully realize its potential to reduce electricity purchases,

and if they are above this range, additional production will require more advanced energy management systems (EMS), energy storage, or demand flexibility.

The results also indicate that expanding power generation beyond 22 MWp is not just about increasing installed capacity but rather a transition to a more complex university energy management system that requires rigorous oversight, real-time monitoring, load management, battery energy storage systems (BESS), and demand response. Each process is considered critical. The initial installation of solar panels can immediately reduce scope 2 greenhouse gas emissions, while investments in energy management systems (EMS) and battery energy storage systems (BESS) should be considered with consideration of real-world usage constraints to manage the risk of excess generation (curtailment) and the university's readiness to handle higher renewable energy use. Therefore, a technical feasibility assessment alone is insufficient; the university's operational capacity must determine how far and how quickly it can scale its renewable energy strategy.

The methodological contribution of this research lies in treating strategic diagnosis and technical assessment as interdependent components of university carbon reduction planning, rather than starting with technology adoption alone. The proposed approach begins by examining the greenhouse gas emissions structure, the university context, spatial capacity, and operational readiness. This is then used to identify key measures and assess appropriate deployment sizes, providing a practical planning logic for Thai universities facing similar constraints, particularly those with high electricity demand, large campus areas, fragmented information systems, and limited investment flexibility. The KKU case study thus presents more than just a site-specific solar energy assessment; it demonstrates that carbon neutrality planning can lead to a gradual, evidence-based approach. And it is institutionally feasible.

However, three limitations should be noted. Firstly, the solar energy assessment relies on annual load and solar volume data, which may not fully record seasonal variations, especially during the monsoon season in northeastern Thailand. Secondly, while a preliminary LCOE and simple payback screening is provided (Section 3.7), it does not include a full internal rate of return (IRR) or discounted cash-flow analysis, which would require detailed CAPEX quotations and is necessary for final investment decisions. Thirdly, battery energy storage systems (BESS) and high-demand response scenarios are not simulated, although prior residential and campus-scale evidence indicates that BESS integration can further

raise SCR once curtailment becomes material (Vieira et al., 2017; Weniger et al., 2014). These limitations constrain the 19–22 MWp range to the initial installation size under current data, policies, and infrastructure conditions, rather than serving as the final ceiling for KKU's long-term carbon reduction path. Future research should extend this assessment with hourly simulations that incorporate battery energy storage systems (BESS), demand response, a full discounted cash-flow feasibility study, and campus microgrid scenarios.

6. Conclusion

This study developed an energy management strategic framework for Khon Kaen University's transition toward carbon neutrality, integrating strategic planning analysis with technical solar PV assessment within a single systematic investigation. The study confirms that KKU's strategic planning must be grounded in an organizational understanding of emission structure, energy consumption patterns, spatial resource availability, carbon sequestration potential, and management system readiness—rather than in a simple aggregation of available mitigation measures.

The energy sector is the most strategically critical dimension for KKU, given the primacy of purchased electricity in the university's GHG emission profile. The proposed energy management strategy is structured around four integrated components: renewable energy integration, building energy efficiency improvement, load and grid management, and data and MRV development. Among all feasible energy measures, solar PV is confirmed as the most appropriate flagship measure, combining strategic significance, technical suitability, and site availability across multiple installation modalities.

The technical assessment identifies 19–22 MWp as the optimal practical capacity range, yielding SCR values of 98.9–99.7%, SSR values of 26–30%, and curtailment rates of 0.27–1.08%—all of which satisfy international performance benchmarks without requiring BESS in the initial phase. In absolute terms, this capacity range delivers a direct GHG reduction of approximately 13,300–15,300 tCO₂e/yr (≈26–30% of KKU's electricity-related emissions) and ≈16–19% of total institutional emissions), and remains technically valid under a projected 2040 load scenario, confirming it as a robust Phase 1 measure on KKU's pathway to carbon neutrality by 2040 and, ultimately, net zero.

For policy and practice, this study proposes that Thai universities adopt a strategy-led implementation approach: beginning with an analysis of emission structures and institutional context; synthesizing strategic dimensions and priority measures; selecting flagship measures supported by both systemic significance and technical evidence; and developing supporting infrastructure—including EMS, smart grid capabilities, and MRV systems—to sustain long-term progress. The central lesson from KKU is that a net-zero campus pathway becomes actionable when the significance of emissions, technical feasibility, spatial capacity, and institutional readiness are evaluated together.

Future research should extend this initial strategic assessment with hourly simulations that incorporate BESS, demand response, financial feasibility, and campus microgrid scenarios. Such work would help clarify how universities can move beyond initial Scope 2 reductions toward deeper decarbonization under real operational, financial, and infrastructure constraints.

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Human Subjects

This study did not involve human subjects. All data used in the analysis were obtained from institutional records and publicly available databases.

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Data Availability Statement

Data may be obtained from the corresponding author upon reasonable written request, subject to institutional data-sharing policies.

Use of Generative Artificial Intelligence (AI) and AI-Assisted Technologies

During manuscript preparation, AI-assisted tools were used only for language refinement and editorial polishing. The research design, data collection, analytical procedures, interpretation of findings, conclusions, and scholarly judgments were developed and verified by the authors. The authors reviewed and approved the final manuscript and take full responsibility for its accuracy, integrity, and originality.

CRediT with degree of contribution:

Watchara Pattanawiwattanaporn: Conceptualization; Methodology; Validation; Formal analysis; Investigation; Resources; Data curation; Writing – original draft; Writing – review and editing; Visualization; Project administration.
Choopong Thongkumsamut : Conceptualization; Methodology; Validation; Resources; Writing – review and editing; Supervision; Project administration; Funding acquisition.



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References

- Aghamolaei, R., & Fallahpour, M. (2023). Strategies towards reducing carbon emission in university campuses: A comprehensive review of both global and local scales. *Journal of Building Engineering*, 76, Article 107183. <https://doi.org/10.1016/j.jobee.2023.107183>
- Ali, A., Muqet, H. A., Khan, T., Hussain, A., Waseem, M., & Niazi, K. A. K. (2023). IoT-enabled campus prosumer microgrid energy management: A comprehensive study. *Energies*, 16(4), Article 1863. <https://doi.org/10.3390/en16041863>
- Amin, M. M., & Kocher, I. S. (2023). Floating photovoltaic performance evaluation using novel cooling system case study. *NTU Journal of Renewable Energy*, 5(1), 86–92. <https://doi.org/10.56286/ntujre.v5i1.624>
- Bertsch, V., Geldermann, J., & Lühn, T. (2017). What drives the profitability of household PV investments, self-consumption and self-sufficiency? *Applied Energy*, 204, 1–15. <https://doi.org/10.1016/j.apenergy.2017.06.055>

- Cao, S., Hasan, A., & Sirén, K. (2016). Nearly zero-energy building in Finland—energy performance and net zero-energy concept. *Energy*, 116, 734–752. <https://doi.org/10.1016/j.energy.2016.09.143>
- Castillo-Cagigal, M., Caamaño-Martín, E., Matallanas, E., Masa-Bote, D., Gutiérrez, A., Monasterio-Huelin, F., & Jiménez-Leube, J. (2011). PV self-consumption optimization with storage and active DSM for the residential sector. *Solar Energy*, 85(9), 2338–2348. <https://doi.org/10.1016/j.solener.2011.06.028>
- Del Borghi, A., Spiegelhalter, T., Moreschi, L., & Gallo, M. (2021). Carbon-neutral-campus building: Design versus retrofitting of two university zero energy buildings in Europe and in the United States. *Sustainability*, 13(16), Article 9023. <https://doi.org/10.3390/su13169023>
- Denholm, P., & Margolis, R. M. (2007). Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies. *Energy Policy*, 35(9), 4424–4433. <https://doi.org/10.1016/j.enpol.2007.03.004>
- Depietri, Y., & McPhearson, T. (2017). Integrating the grey, green, and blue in cities: Nature-based solutions for climate change adaptation and risk reduction. In N. Kabisch, H. Korn, J. Stadler, & A. Bonn (Eds.), *Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice* (pp. 91–109). Springer. https://doi.org/10.1007/978-3-319-56091-5_6
- Eltawil, M. A., & Zhao, Z. (2010). Grid-connected photovoltaic power systems: Technical and potential problems—A review. *Renewable and Sustainable Energy Reviews*, 14(1), 112–129. <https://doi.org/10.1016/j.rser.2009.07.015>
- Evans, J., Jones, R., Karvonen, A., Millard, L., & Wendler, J. (2015). Living labs and co-production: University campuses as platforms for sustainability science. *Current Opinion in Environmental Sustainability*, 16, 1–6. <https://doi.org/10.1016/j.cosust.2015.06.005>
- Filho, W. L., Salvia, A. L., Frankenberger, F., Akib, N. A. M., & Pallant, E. (2021). Sustainability and renewable energy at universities: Experiences from North America. *International Journal of Sustainable Development & World Ecology*, 28(4), 331–341. <https://doi.org/10.1080/13504509.2020.1860315>
- Filho, W. L., Weissenberger, S., Luetz, J. M., Sierra, J., Rampasso, I. S., Sharifi, A., et al. (2023). Towards a greater engagement of universities in addressing climate change challenges. *Scientific Reports*, 13, Article 19030. <https://doi.org/10.1038/s41598-023-45866-x>
- Fox, W., Dwivedi, P., Lowe, R. C., III, Welch, S., & Fuller, M. (2020). Estimating carbon stock of live trees located on the main campus of the University of Georgia. *Journal of Forestry*, 118(5), 457–465. <https://doi.org/10.1093/jofore/fvaa025>
- Gacu, J. G., Garcia, J. D., Fetalvero, E. G., Catajay-Mani, M. P., & Monjardin, C. E. F. (2023). Suitability analysis using GIS-based analytic hierarchy process for solar power exploration. *Energies*, 16(18), Article 6724. <https://doi.org/10.3390/en16186724>
- Gao, L., Wang, S., Mao, M., Liu, C., & Li, T. (2024). Study on the energy consumption characteristics and the self-sufficiency rate of rooftop photovoltaic of university campus buildings. *Energies*, 17(14), Article 3535. <https://doi.org/10.3390/en17143535>
- Guerrieri, M., La Gennusa, M., Peri, G., Rizzo, G., & Scaccianoce, G. (2019). University campuses as small-scale models of cities: Quantitative assessment of a low carbon transition path. *Renewable and Sustainable Energy Reviews*, 113, Article 109263. <https://doi.org/10.1016/j.rser.2019.109263>
- Halder, B., Banik, P., Almohamad, H., Al Dughairi, A. A., Al-Mutiry, M., Al Shahrani, H. F., & Abdo, H. G. (2022). Land suitability investigation for solar power plant using GIS, AHP and multi-criteria decision approach: A case of megacity Kolkata, West Bengal, India. *Sustainability*, 14(18), Article 11276. <https://doi.org/10.3390/su141811276>
- Helmets, E., Chang, C.-C., & Dauwels, J. (2021). Carbon footprinting of universities worldwide: Part I—Objective comparison by standardized metrics. *Environmental Sciences Europe*, 33(1), Article 30. <https://doi.org/10.1186/s12302-021-00454-6>
- International Renewable Energy Agency. (2017). Electricity storage and renewables: Costs and markets to 2030. IRENA.
- Islam, M. S., Liu, G., Xu, D., Chen, Y., Li, H., & Chen, C. (2023). University-campus-based zero-carbon action plans for accelerating the zero-carbon city transition. *Sustainability*, 15(18), Article 13504. <https://doi.org/10.3390/su151813504>
- Kohl, K., Hopkins, C., Barth, M., Michelsen, G., Dlouha, J., Razak, D. A., Sanusi, Z. A. B., & Toman, I. (2022). A whole-institution approach towards sustainability: A crucial aspect of higher education's individual and collective engagement with the SDGs and beyond. *International Journal of Sustainability in Higher Education*, 23(2), 218–236. <https://doi.org/10.1108/IJSHE-10-2020-0398>

- Leal Filho, W., Weissenberger, S., Luetz, J. M., Sierra, J., Rampasso, I. S., Sharifi, A., Anholon, R., Eustachio, J. H. P. P., & Kovaleva, M. (2023). Towards a greater engagement of universities in addressing climate change challenges. *Scientific Reports*, 13, Article 19030. <https://doi.org/10.1038/s41598-023-45866-x>
- Li, Y., & Jia, Q. S. (2022). On the feasibility to achieve carbon neutrality in university campus: A case study. *IFAC-PapersOnLine*, 55(5), 78–83. <https://doi.org/10.1016/j.ifacol.2022.07.643>
- Lin, X., Cai, H., & Zhao, S. (2024). An empirical analysis of carbon emissions in higher education institutions: A case study of Zhejiang Ocean University using emission factor methodology. *Sustainability*, 16(21), Article 9412. <https://doi.org/10.3390/su16219412>
- Luthander, R., Widén, J., Nilsson, D., & Palm, J. (2015). Photovoltaic self-consumption in buildings: A review. *Applied Energy*, 142, 80–94. <https://doi.org/10.1016/j.apenergy.2014.12.028>
- Nottrott, A., Kleissl, J., & Washom, B. (2013). Energy dispatch schedule optimization and cost benefit analysis for grid-connected, photovoltaic-battery storage systems. *Renewable Energy*, 55, 230–240. <https://doi.org/10.1016/j.renene.2012.12.036>
- Office of Natural Resources and Environmental Policy and Planning. (2021). Thailand's long-term low greenhouse gas emission development strategy. ONEP.
- Paredes-Canencio, K. N., Lasso, A., Castrillon, R., Vidal-Medina, J. R., & Quispe, E. C. (2024). Carbon footprint of higher education institutions: A review. *Environment, Development and Sustainability*, 26, 30239–30272. <https://doi.org/10.1007/s10668-024-04596-4>
- Paspatis, A., Fiorentzis, K., Katsigiannis, Y., & Karapidakis, E. (2022). Smart campus microgrids towards a sustainable energy transition—The case study of the Hellenic Mediterranean University. *Mathematics*, 10(7), Article 1065. <https://doi.org/10.3390/math10071065>
- Quoilin, S., Kavvadias, K., Mercier, A., Pappone, I., & Zucker, A. (2016). Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. *Applied Energy*, 182, 58–67. <https://doi.org/10.1016/j.apenergy.2016.08.077>
- Sachs, J., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six transformations to achieve the sustainable development goals. *Nature Sustainability*, 2(9), 805–814. <https://doi.org/10.1038/s41893-019-0352-9>
- Salpakari, J., & Lund, P. (2016). Optimal and rule-based control strategies for energy flexibility in buildings with PV. *Applied Energy*, 161, 425–436. <https://doi.org/10.1016/j.apenergy.2015.10.111>
- Salom, J., Marszal, A. J., Widén, J., Candanedo, J., & Lindberg, K. B. (2014). Analysis of load match and grid interaction indicators in net zero energy buildings. *Applied Energy*, 136, 119–131. <https://doi.org/10.1016/j.apenergy.2014.09.018>
- Sarasa-Maestro, C. J., Dufo-López, R., & Bernal-Agustín, J. L. (2016). Analysis of photovoltaic self-consumption systems. *Energies*, 9(9), Article 681. <https://doi.org/10.3390/en9090681>
- Suganthi, D., & Jamuna, K. (2025). Optimizing campus microgrid energy systems: Economic, environmental, and sensitivity insights. *Energy Conversion and Management: X*, 27, Article 101046. <https://doi.org/10.1016/j.ecmx.2025.101046>
- Thailand Greenhouse Gas Management Organization. (2024). Emission factors for carbon footprint assessment of organizations. TGO.
- Vieira, F. M., Moura, P. S., & Almeida, A. T. (2017). Energy storage system for self-consumption of photovoltaic energy in residential zero energy buildings. *Renewable Energy*, 103, 308–320. <https://doi.org/10.1016/j.renene.2016.11.048>
- Wang, L., Yan, X., Fang, M., Song, H., & Hu, J. (2023). A systematic design framework for zero carbon campuses: Investigating the Shanghai Jiao Tong University Fahu Campus case. *Sustainability*, 15(10), Article 7975. <https://doi.org/10.3390/su15107975>
- Weniger, J., Tjaden, T., & Quaschnig, V. (2014). Sizing of residential PV battery systems. *Energy Procedia*, 46, 78–87. <https://doi.org/10.1016/j.egypro.2014.01.160>
- Yang, P., Chua, L. H. C., Irvine, K. N., & Su, S. L. (2022). Impacts of a floating photovoltaic system on temperature and water quality in a shallow tropical reservoir. *Limnology*, 23, 441–454. <https://doi.org/10.1007/s10201-022-00698-y>