

Article

An Integrated LEAP–InVEST Framework for MRV-Aligned Carbon Neutrality Planning: A Case Study of National Dong Hwa University, Taiwan

Amit Kumar Sah ¹ , Yao-Ming Hong ^{1,*}  and Su Hwa Lin ^{2,*}¹ Department of Natural Resources and Environmental Studies, National Dong Hwa University, Hualien 974301, Taiwan; sahamit644@gms.ndhu.edu.tw² Department of Science Education and Application, National Taichung University of Education, Taichung 403514, Taiwan

* Correspondence: hongyaoming@gms.ndhu.edu.tw (Y.-M.H.); shlin0517@gmail.com (S.H.L.)

Abstract

Universities worldwide are increasingly committing to carbon neutrality; however, most institutional climate strategies treat operational emissions forecasting and ecosystem-based carbon sequestration as separate analytical domains, leading to inconsistencies in accounting boundaries, temporal alignment, and verification practices. This study develops and demonstrates an integrated LEAP–InVEST framework that explicitly links energy-system modeling with spatial ecosystem carbon accounting within a unified monitoring, reporting, and verification (MRV)-aligned structure. The framework combines the Low Emissions Analysis Platform (LEAP) for scenario-based greenhouse gas emissions modeling with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model for spatial carbon storage assessment. A key methodological contribution lies in reconciling emission flows and carbon stock changes by converting carbon stock variations into annualized removal flows, thereby enabling consistent estimation of gross emissions, carbon removals, and net emissions while avoiding double counting across scopes. Using a university campus in Taiwan as a case study, a baseline inventory was established following ISO 14064-1 standards, and future emissions trajectories were simulated under Business-as-Usual and mitigation pathways through 2040. In parallel, land-use and land-cover data were used to quantify historical and projected carbon stocks across forest, grassland, agricultural, and built-up areas. Results indicate that electricity consumption constitutes the dominant emissions source, and that energy efficiency improvements, photovoltaic deployment, and green power procurement provide the largest mitigation potential. Although ecosystem carbon stocks remain substantial, their annual sequestration capacity offsets only a limited portion of projected emissions, reinforcing the importance of prioritizing emissions reduction before applying nature-based removals. The proposed framework provides a transferable methodological approach for institutional carbon neutrality planning by integrating emissions reduction and carbon sequestration within a coherent analytical system. By aligning energy modeling, ecosystem dynamics, and MRV principles, the framework enhances the transparency, credibility, and robustness of net-zero pathway assessment and is applicable to universities and compact urban systems seeking data-driven and verifiable decarbonization strategies.



Academic Editor: Antonio Caggiano

Received: 3 April 2026

Revised: 24 April 2026

Accepted: 30 April 2026

Published: 4 May 2026

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Keywords: institutional decarbonization; greenhouse gas scenario modeling; carbon storage; land use and land cover change; nature-based solutions; net-zero accounting; sustainability; Taiwan climate policy

1. Introduction

The global transition toward net-zero emissions has accelerated rapidly over the past decade, driven by increasing alignment between national climate commitments and science-based decarbonization pathways [1–3]. Within this broader transformation, higher education institutions have emerged as critical actors in climate mitigation, not only because of their operational carbon footprints but also due to their unique capacity to function as living laboratories for low-carbon transition strategies [3–5]. At the campus scale, empirical analyses have demonstrated that combining photovoltaic deployment with expanded vegetation cover can make carbon neutrality technically and financially feasible within a single decade, even for large research-intensive universities with electricity-dominated emission profiles [3]. University campuses, characterized by integrated energy systems, transportation networks, built infrastructure, and managed ecosystems, represent compact socio-ecological systems that closely resemble small urban environments. As such, they offer an ideal context for developing and testing comprehensive carbon neutrality pathways.

University campuses are particularly suited to this type of integrated assessment for four reasons. First, they function as compact socio-ecological systems with well-defined organizational and spatial boundaries, enabling closed-boundary emissions accounting without the jurisdictional complexity that complicates municipal or regional analyses. Second, their emission profiles span all major source categories—electricity, direct combustion, fugitive refrigerants, and waste—at a scale where verified inventory data are routinely collected, making them ideal calibration contexts for LEAP-based scenario modeling. Third, their managed landscapes encompass diverse land-cover types whose carbon dynamics can be quantified spatially using the InVEST model, enabling direct integration with emissions projections. Fourth, the methodological components of this framework—inventory-based LEAP calibration, multi-temporal InVEST carbon stock analysis, MOLUSCE-based LULC projection, and sequential scenario stacking—are each operationally replicable by any institution with access to open-source satellite LULC data and standard campus GHG inventory records, making the framework transferable to other higher education institutions and compact urban systems.

Despite growing institutional commitments to carbon neutrality, methodological inconsistencies remain in how emissions reduction and carbon sequestration are jointly conceptualized and operationalized. Most universities adopt greenhouse gas (GHG) inventories based on internationally recognized standards such as ISO 14064-1 [6] and the GHG Protocol, which provide robust frameworks for quantifying direct (Scope 1), indirect (Scope 2), and selected upstream emissions (Scope 3) [7]. While these approaches ensure transparency and accountability, they are predominantly retrospective in nature and do not inherently support forward-looking evaluation of decarbonization pathways [8]. Scenario-based energy system models, such as the Low Emissions Analysis Platform (LEAP), have been widely applied at national and regional scales to simulate long-term emissions trajectories under alternative policy and technology assumptions [9,10]. However, their application at the institutional scale remains limited, and their integration with ecosystem-based carbon accounting has not been systematically addressed.

Concurrently, nature-based solutions have gained increasing attention as complementary mitigation strategies, emphasizing the role of land-use management, ecosystem restoration, and carbon sequestration in achieving net-zero targets [11–13]. The carbon sink potential of diverse ecosystem types—including forests, coastal wetlands, and marine environments—has been extensively quantified at regional scales, demonstrating that nature-based removal pathways can contribute meaningfully to provincial and sub-national carbon neutrality strategies when integrated with emission reduction planning [13]. Spatially explicit ecosystem service models such as the Integrated Valuation of Ecosystem Ser-

vices and Tradeoffs (InVEST) enable the quantification of carbon storage across land-use categories and have been widely applied in landscape-scale and regional assessments [14–17]. Nevertheless, these models typically produce static estimates of carbon stocks rather than dynamic annual sequestration flows, limiting their compatibility with emissions scenario modeling frameworks. As a result, operational emissions modeling and ecosystem carbon assessments are often conducted in isolation, leading to fragmented and potentially inconsistent representations of net-zero pathways.

This disconnection gives rise to three fundamental methodological challenges. First, inconsistencies in system boundaries between emissions inventories and ecosystem assessments may lead to double counting or misalignment between gross emissions and removals. Second, a temporal mismatch exists between annual emission flows and static carbon stock estimates, complicating the integration of reductions and removals within a unified accounting framework. Third, existing approaches lack alignment with monitoring, reporting, and verification (MRV) principles, which are essential for ensuring credibility and comparability of net-zero claims. Robust MRV systems require clear standards for monitoring boundaries, consistent reporting methodologies, and independent verification processes; yet existing frameworks often reveal significant gaps in documentation detail and protocol standardization that compromise the reliability of carbon credit claims across different institutional and geographic contexts [18]. Beyond technical protocol design, the effectiveness of MRV systems is also deeply shaped by institutional design and the professionalism of those implementing them—data manipulation and principal–agent failures in carbon reporting have been documented even in well-resourced national carbon markets, underscoring that transparency and accountability mechanisms must be embedded in any credible MRV framework [19]. These limitations are particularly critical in electricity-dominated systems, where overreliance on carbon sequestration may lead to overestimation of mitigation potential relative to demand-side and supply-side energy interventions [20]. Although prior studies have examined campus sustainability and decarbonization strategies [21,22], there remains a lack of integrated methodological frameworks that reconcile emissions reductions and ecosystem-based removals within a consistent analytical structure. Specifically, this study addresses three research questions: (RQ1) How can operational GHG emissions modeling and spatial ecosystem carbon stock assessment be integrated within a consistent accounting boundary to evaluate institutional carbon neutrality pathways? (RQ2) What is the relative contribution of energy-system interventions versus nature-based carbon removals to achieving campus-scale net-zero? (RQ3) Under what scenario assumptions and parameter conditions can an electricity-dominated institutional system achieve carbon neutrality by 2040, and how sensitive are these outcomes to key modeling uncertainties?

To address these gaps, this study develops an integrated dual-model framework that combines LEAP-based emissions scenario analysis with InVEST-based spatial carbon storage assessment to evaluate institutional carbon neutrality pathways. Using National Dong Hwa University (NDHU) in Taiwan as a case study, a verified baseline GHG inventory was first established following ISO 14064-1 standards to ensure consistency with international accounting practices. Future emissions trajectories were then simulated under Business-as-Usual and mitigation scenarios through 2040 using LEAP, incorporating energy efficiency improvements, photovoltaic deployment, refrigerant management, and electricity procurement strategies. In parallel, land-use and land-cover (LULC) data were used to quantify historical and projected carbon stocks using InVEST, and these results were translated into annualized carbon removal estimates compatible with emissions modeling.

This study pursues three objectives. First, it develops a unified analytical framework that integrates LEAP-based emissions scenario analysis with InVEST-based spatial carbon

stock assessment within a consistent accounting boundary. Second, it operationalizes this framework by applying it to National Dong Hwa University (NDHU) Shoufeng Campus in Taiwan, using a verified 2023 ISO 14064-1 greenhouse gas inventory as the empirical foundation and multi-temporal Sentinel-2 LULC data as the spatial basis for carbon stock estimation. Third, it evaluates two integrated decarbonization pathways through 2040 and assesses the sensitivity of net-zero outcomes to key parameter uncertainties, contributing a transferable methodology for institutional carbon neutrality planning.

The remainder of this paper is organized as follows. Section 2 presents the integrated modeling framework and describes its application to the NDHU case. Section 3 reports InVEST carbon stock results and LEAP scenario and pathway results. Section 4 discusses structural insights, framework transferability, and MRV implications. Section 5 concludes. Section 6 outlines limitations and future research directions.

2. Materials and Methods

This study employs a dual-model framework that integrates both operational emission forecasting and spatial ecosystem service modeling to construct a comprehensive carbon neutrality pathway for NDHU. The methodological design consists of two parallel but interconnected modeling components: the LEAP (Version: 2024.4.0.15) for carbon emission accounting and mitigation scenario planning, and the InVEST (Version: 3.15.1) model for land-based carbon storage and sequestration estimation. Together, these tools provide a robust assessment of carbon sources and sinks on NDHU's Shoufeng Campus.

The integrated LEAP–InVEST framework developed in this study consists of five sequential steps, illustrated in Figure 1. Step 1 (Boundary and Temporal Alignment) defines the spatial and organizational study boundary and establishes the temporal framework for both model components. Step 2 (LULC Acquisition and Carbon Stock Estimation) acquires multi-temporal satellite LULC data, processes them within a GIS environment, and applies the InVEST Carbon Storage module to estimate carbon stocks for each observation year. Step 3 (Future LULC Projection) uses the MOLUSCE plugin to simulate future land-cover conditions and runs InVEST in sequestration mode to estimate net carbon stock changes relative to the reference year. Step 4 (Emissions Baseline and Scenario Modeling) establishes the verified GHG inventory as the LEAP baseline, constructs the BAU trajectory, and simulates individual mitigation scenarios. Step 5 (Integration and Pathway Construction) converts InVEST carbon stock changes into annualized sequestration flows, incorporates these as negative emissions in LEAP, and constructs integrated decarbonization pathways. Sections 2.1–2.3 describe the application of each step to the NDHU Shoufeng Campus case.

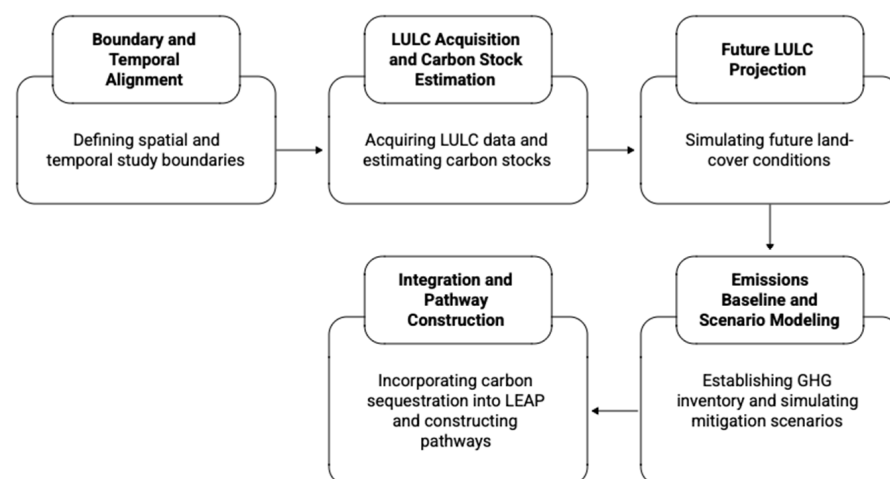


Figure 1. Integrated LEAP–InVEST framework workflow.

2.1. Study Boundary and Time Horizon

NDHU is in Shoufeng Township, Hualien County, Taiwan, and covers approximately 251 hectares. The campus is situated within a humid subtropical climate zone influenced by the East Asian monsoon system, with an annual average temperature of approximately 22 °C and annual precipitation exceeding 2000 mm [23]. Elevation across the campus ranges from 30 to 120 m above sea level. The spatial boundary of this study is strictly confined to the Shoufeng Campus, and all operational emissions (LEAP model) and terrestrial carbon stock assessments (InVEST model) are limited to this defined institutional boundary to ensure consistent accounting and avoid spatial discrepancies.

LULC within the campus were identified using Sentinel-2 10-m resolution classification data produced by Esri and Impact Observatory. The campus landscape comprises a heterogeneous mixture of tree-covered areas, croplands, built-up infrastructure, rangelands, water bodies, flooded vegetation, and limited exposed soil areas. Tree-covered areas dominate the southeastern and peripheral regions and consist primarily of secondary growth forests and regenerated vegetation. Built-up areas, including academic buildings, administrative facilities, dormitories, and transportation infrastructure, are concentrated in the northern and central zones. Agricultural plots and croplands are distributed across managed research areas, while water bodies and flooded vegetation occur primarily in western and central sections, serving ecological and irrigation functions. Classes such as snow/ice and cloud cover appearing in the satellite dataset were excluded from analysis as they represent atmospheric artifacts rather than actual land cover. The diversity of land cover types provides a suitable spatial context for evaluating variations in carbon storage across vegetation, soil, and developed land categories.

Figure 2 presents the spatial context of the study area, illustrating the location of Hualien County within Taiwan and the delineated boundary of the Shoufeng Campus used for model implementation. The same geographic boundary was applied consistently in both LEAP and InVEST analyses to ensure alignment between operational emissions and ecosystem carbon accounting.

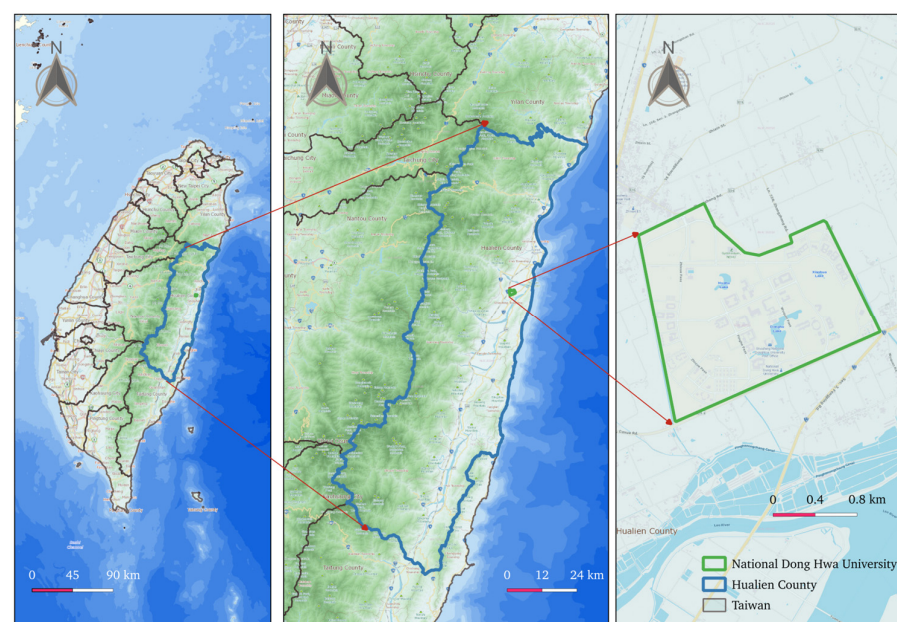


Figure 2. Study Area.

The temporal framework of the study differs slightly between operational emissions modeling and ecosystem carbon assessment due to methodological distinctions between the two tools. The LEAP model adopts 2023 as the base year, corresponding to the most recent

verified greenhouse gas inventory, and projects emissions annually through 2040 in alignment with the institutional carbon neutrality target. Interim milestone years (2030 and 2035) are incorporated to evaluate medium-term mitigation progress. In contrast, the InVEST model applies a historical and predictive LULC-based approach. Carbon storage was estimated for 2018, 2020, 2022, and 2024 to establish recent stock dynamics, while future LULC scenarios were simulated for 2026 and 2030 using the MOLUSCE plugin in QGIS. It is important to acknowledge a temporal mismatch between the two model components: InVEST-based carbon stock estimates are empirically grounded through 2030, whereas LEAP emissions projections extend through 2040. Sink capacity values applied in the integrated pathways for 2035 and 2040 therefore represent scenario-informed extrapolations rather than direct InVEST outputs, and are bounded by area-based biomass accumulation rates documented for subtropical forests in eastern Taiwan [24]. These projections enable assessment of short- to medium-term terrestrial carbon stock changes, which are subsequently integrated into the emissions modeling framework. Although ecosystem projections do not extend to 2040, the derived sequestration estimates provide essential inputs for evaluating near-term carbon sink contributions and residual emission management within the LEAP scenarios.

2.2. InVEST Model Framework for Carbon Sequestration Estimation

To quantify the spatial distribution and temporal dynamics of carbon storage across the NDHU Shoufeng Campus, the Carbon Storage and Sequestration module of the InVEST model was employed. InVEST is an open-source, GIS-based modeling platform developed by the Natural Capital Project for assessing ecosystem services such as carbon storage, habitat quality, and water yield. In this study, the carbon module was used to estimate total carbon stocks associated with different land use and land cover (LULC) classes and to evaluate changes in carbon storage resulting from observed and projected land transitions. The model enables spatially explicit quantification of carbon pools and provides a consistent framework for linking land-use dynamics with climate mitigation potential at institutional scale.

2.2.1. Land Use/Land Cover (LULC) Data Acquisition and Processing

Multi-temporal LULC datasets were obtained from the Sentinel-2 10-m Land Cover Time Series produced collaboratively by Esri, Impact Observatory, and Microsoft. LULC maps for 2018, 2020, 2022, and 2024 were downloaded in GeoTIFF format and processed using QGIS 3.28. These datasets provide standardized classification outputs suitable for spatio-temporal comparison of land cover change. All raster layers were clipped to the officially delineated NDHU Shoufeng Campus boundary to ensure that carbon stock estimation was restricted to land under institutional management. The campus boundary was digitized using updated basemaps and verified against official campus spatial references. To ensure spatial consistency, all raster datasets were reprojected to the Universal Transverse Mercator coordinate system (UTM Zone 51N; EPSG:32651), which is appropriate for area-based analysis in Taiwan. The rasters were further aligned to a consistent spatial extent and maintained at a 10-m resolution to preserve comparability across time steps.

The classification scheme included the dominant land cover types present on campus: water (class 1), trees (class 2), flooded vegetation (class 4), cropland (class 5), built-up area (class 7), bare ground (class 8), and rangeland (class 11). Classes representing atmospheric artifacts, such as clouds (class 10), were excluded from analysis, and non-representative classes such as snow/ice were omitted due to their absence within the study area. Pixels outside the campus boundary were assigned NoData values to ensure that all subsequent carbon calculations reflect on-site land dynamics only. The resulting LULC maps provide a consistent spatial dataset for evaluating land-use transitions across the study period. The

processed LULC maps for 2018, 2020, 2022, and 2024 are presented in Figure 3. Observed changes in vegetation cover, infrastructure expansion, and managed agricultural areas directly inform the carbon storage estimates generated by InVEST. These LULC datasets serve as the foundational input for quantifying carbon pools and assessing the influence of land-use change on terrestrial carbon sequestration within the campus boundary.

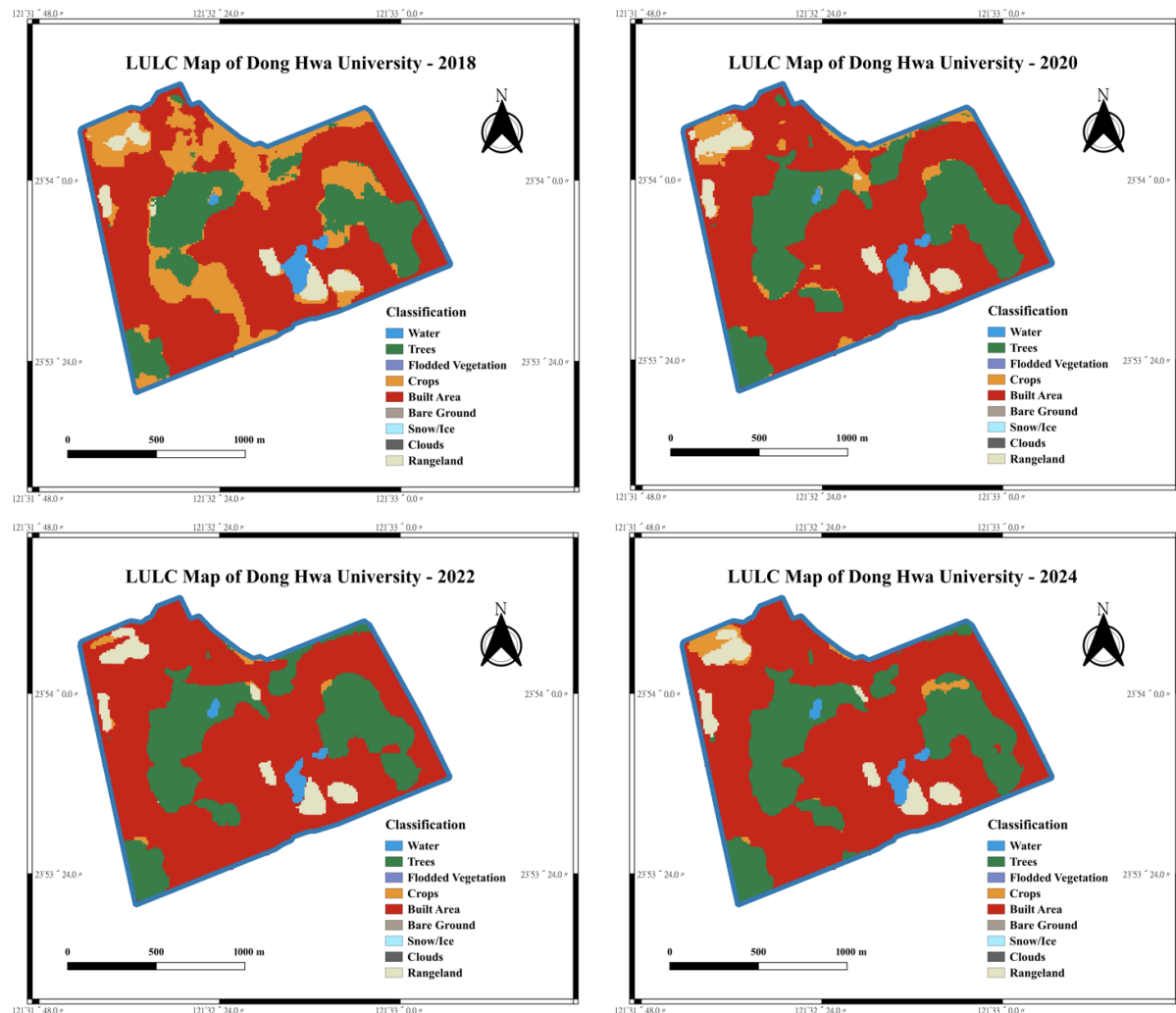


Figure 3. Land Use Land Cover (LULC) maps of National Dong Hwa University for the years 2018, 2020, 2022, and 2024.

To complement the spatial interpretation of land use dynamics, Table 1 summarizes the quantitative distribution of major land cover classes within the NDHU Shoufeng Campus for the years 2018, 2020, 2022, and 2024. The table reports both absolute area (hectares) and proportional coverage (%) derived from the processed LULC rasters. Over the study period, notable shifts were observed among key land categories. Tree-covered areas increased substantially from 18.25% (43.38 ha) in 2018 to 25.92% (61.62 ha) in 2020, representing an increase of approximately 18 hectares over two years. This rapid expansion coincides with a simultaneous and pronounced decline in cropland from 21.26% (50.54 ha) to 5.22% (12.41 ha) over the same period, suggesting that a portion of former agricultural land underwent vegetation recovery and was subsequently reclassified as tree cover in the Sentinel-2 classification. This transition is ecologically plausible in the subtropical humid climate of Hualien, where secondary vegetation regeneration on abandoned or reduced-management agricultural plots can occur relatively rapidly, and where the 10-m resolution Sentinel-2 classification may capture early-stage woody regrowth as tree cover once canopy

closure reaches the detection threshold of the classification algorithm. From 2020 onward, tree cover stabilizes at approximately 25–26% across all subsequent observation years, confirming that the 2018–2020 transition represents a genuine land-cover shift rather than a classification artifact, and that the expanded vegetated area persists through the study period. Built-up areas exhibited a consistent upward trend, expanding from 55.24% in 2018 to 65.98% in 2024, reflecting continued campus infrastructure development. These quantified transitions are critical inputs to the InVEST carbon storage model, as changes among vegetated, agricultural, and built-up classes directly influence aboveground biomass, belowground biomass, and soil carbon pools. Consequently, the temporal evolution of land cover captured in Table 1 provides the empirical basis for estimating changes in total campus carbon stocks across the study period.

Table 1. Area of different classes from the LULC map.

Class	2018 Area (ha)	2018 (%)	2020 Area (ha)	2020 (%)	2022 Area (ha)	2022 (%)	2024 Area (ha)	2024 (%)
Water	3.60	1.51	3.34	1.40	2.90	1.22	3.10	1.30
Trees	43.38	18.25	61.62	25.92	60.97	25.65	61.67	25.94
Crops	50.54	21.26	12.41	5.22	2.10	0.88	5.22	2.20
Built Area	131.31	55.24	149.04	62.69	161.52	67.94	156.86	65.98
Rangeland	8.89	3.74	11.32	4.76	10.24	4.31	10.88	4.58

2.2.2. Future LULC Prediction Using the MOLUSCE Plugin

Future LULC scenarios were simulated using the MOLUSCE (Modules for Land Use Change Simulation) plugin in QGIS. MOLUSCE enables spatially explicit land transition modeling based on historical LULC change patterns and environmental drivers. In this study, classified LULC maps from 2018 and 2020 were used to calibrate transition probabilities between land classes using an artificial neural network (ANN) algorithm. The trained model generated a transition matrix that was subsequently applied to produce a projected LULC map for 2026. Similarly, the 2020 and 2022 LULC datasets were used to simulate land cover conditions for 2030, allowing short- to medium-term landscape change to be incorporated into carbon storage projections. To improve simulation realism, spatial driver variables were incorporated into the ANN training process. These drivers included slope, elevation, and distance to roads, derived from digital elevation models and vector infrastructure layers processed within QGIS. Incorporating these variables enhances the spatial allocation of land transitions by accounting for topographic constraints and development accessibility. The predicted LULC maps for 2026 and 2030 were generated as classified raster datasets and subsequently reprojected and formatted to ensure compatibility with the InVEST carbon storage model, maintaining consistent spatial resolution and coordinate reference systems across all temporal layers.

Figure 4 presents the projected LULC map for 2026, illustrating anticipated spatial redistribution of built-up and vegetated areas within the campus boundary. The simulation indicates continued expansion of built-up zones alongside persistence of tree-dominated areas, particularly in peripheral and southern sectors of the campus. These projected LULC maps provide the spatial basis for estimating future carbon storage changes between 2024 and 2026, as well as for subsequent scenario analysis.

Table 2 summarizes the predicted area (hectares) and proportional coverage (%) of major land cover classes for 2026 based on the MOLUSCE simulation. Built-up areas are projected to cover approximately 66.25% of the campus (157.50 hectares), while tree-covered areas remain substantial at 25.80% (61.34 hectares). Rangelands are projected to account for 4.97% of total area, whereas cropland declines to 1.67%, reflecting ongoing land transition dynamics. Water bodies remain relatively stable at 1.30% of campus area. These projected

distributions serve as key inputs for subsequent InVEST carbon modeling, as shifts among vegetated, agricultural, and built-up classes directly influence aboveground biomass, belowground biomass, and soil carbon stocks used in carbon sequestration estimation.

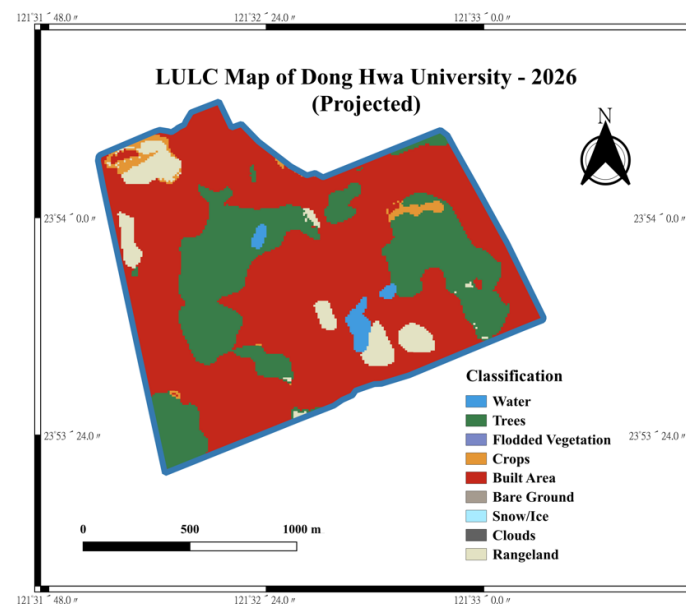


Figure 4. Land Use Land Cover (LULC) maps of National Dong Hwa University for the years 2026.

Table 2. Predicted area and percentage for year 2026.

Class	2026 Area (ha)	2026 (%)
Water	3.10	1.30
Trees	61.34	25.80
Crops	3.98	1.67
Built Area	157.50	66.25
Rangeland	11.81	4.97

2.2.3. Carbon Pool Values and Table Preparation

Carbon storage estimation within the InVEST framework requires the assignment of carbon pool coefficients to each LULC class. In this study, four carbon pools were considered in accordance with the structure of the InVEST Carbon Storage and Sequestration module: aboveground biomass (C_{above}), belowground biomass (C_{below}), soil organic carbon (C_{soil}), and dead organic matter (C_{dead}). These pools represent the principal terrestrial carbon reservoirs contributing to total ecosystem carbon stock and are essential for capturing the structural and functional differences among vegetation, agricultural land, and built-up surfaces.

Carbon stock values expressed in megagrams of carbon per hectare ($Mg\ C\ ha^{-1}$) were assigned to each LULC class identified within the NDHU Shoufeng Campus. The coefficients were primarily derived from IPCC Tier 1 guidelines [24] and supplemented with peer-reviewed literature to ensure ecological consistency under subtropical climatic conditions [17,25]. Where site-specific measurements were unavailable, conservative default values were adopted to maintain methodological transparency and comparability with international carbon accounting practices. Although Tier 2 region-specific or Tier 3 site-measured coefficients would provide greater precision for subtropical forest conditions in eastern Taiwan, such data were unavailable at the institutional scale of this study due to

the absence of campus-level biomass surveys or locally calibrated allometric equations for the dominant vegetation types present on the NDHU Shoufeng Campus. The adoption of Tier 1 defaults therefore represents a practical methodological choice consistent with the spatial resolution and data availability constraints of campus-scale carbon assessments, and is expected to introduce conservative rather than inflated estimates of carbon storage, given that IPCC Tier 1 values for tropical and subtropical forests tend to represent regional averages that may underestimate site-specific biomass accumulation in humid, species-rich environments such as Hualien County [24]. The complete carbon pool coefficient table, including lucode identifiers and corresponding values for each of the four carbon pools, is presented in Table 3. This table serves as a core input parameter for all InVEST model runs conducted in this study.

Table 3. Carbon Pool Table used in this study.

Lucode	Classification	C_Above	C_Below	C_Soil	C_Dead
1	Water	0	0	0	0
2	Trees	80	20	45	5
4	Flooded Vegetation	20	5	40	3
5	Crops	10	5	25	2
7	Built Area	2	0.5	5	0.5
8	Bare Ground	0.5	0.2	10	0.1
9	Snow/Ice	0	0	0	0
10	Clouds	0	0	0	0
11	Rangeland	8	2	30	1

By standardizing carbon pool coefficients across all temporal LULC datasets, the modeling framework ensures that changes in total carbon storage reflect actual land-use transitions rather than variations in parameter assumptions. This approach strengthens the internal consistency of the spatio-temporal carbon stock assessment and facilitates integration with the annual emissions outputs generated by the LEAP model.

2.2.4. Carbon Stock Estimation and Integration with Emissions Modeling

The InVEST Carbon Storage and Sequestration model (v3.13.0) was applied to estimate total carbon stocks and changes across historical and projected land-use conditions within the NDHU Shoufeng Campus. For each selected year (2018, 2020, 2022, and 2024), the model was executed in carbon storage mode to quantify total carbon stored across all land cover classes. To assess future dynamics, comparative simulations were conducted using paired LULC maps to estimate net carbon changes between 2024 and projected scenarios for 2026 and 2030. This approach enables quantification of carbon stock variation resulting from land transitions over time.

Model outputs include spatially explicit estimates of carbon distribution and aggregated summaries of total carbon by land cover category. These outputs were analyzed within a GIS environment to examine spatial patterns and temporal changes in carbon density across the campus. Because InVEST reports carbon quantities in metric tons of carbon (tC), all results were converted to metric tons of carbon dioxide equivalent (tCO₂e) using the standard molecular mass conversion factor (3.667). This harmonization ensures consistency with the LEAP model, which reports operational emissions in tCO₂e, thereby enabling direct comparison and integration within the institutional carbon neutrality framework. The annualized carbon stock changes derived from InVEST were subsequently incorporated as biogenic removals within the integrated LEAP–InVEST modeling structure. This procedure

allows evaluation of net emissions trajectories while maintaining clear separation between fossil-based operational emissions and land-based carbon storage dynamics.

2.2.5. Role of InVEST in the Integrated Framework

Within the overall modeling framework, the InVEST component functions as the spatial carbon sink module that complements scenario-based operational emissions projections. The model results enable identification of high-carbon land cover types and quantification of changes in terrestrial carbon storage across time. Although projections were limited to 2030 due to LULC simulation constraints, the derived carbon stock dynamics provide critical inputs for evaluating the magnitude and reliability of campus-based sequestration relative to projected emissions. This integration strengthens the analytical consistency of the carbon neutrality assessment and supports the development of monitoring and verification structures for land-based carbon management.

2.3. LEAP Model Framework for Emissions and Mitigation Scenarios

To quantify operational greenhouse gas (GHG) emissions and evaluate mitigation pathways for National Dong Hwa University's Shoufeng Campus, this study employed the Low Emissions Analysis Platform (LEAP), a scenario-based energy-environment modeling tool developed by the Stockholm Environment Institute. LEAP is widely used for energy policy analysis, emissions forecasting, and climate mitigation planning across institutional, municipal, and national scales [26–29]. The platform enables construction of a verified baseline inventory, projection of business-as-usual (BAU) trajectories, and simulation of intervention scenarios over defined time horizons. In this study, LEAP was configured to represent the operational emissions structure of the Shoufeng Campus for the base year 2023 and to simulate annual emissions trajectories through 2040, aligned with the university's carbon neutrality target. Eight mitigation scenarios (S1–S8) were developed and subsequently consolidated into two integrated decarbonization pathways (Pathway A and Pathway B) for comparative analysis.

2.3.1. Emission Boundaries and Data Sources

The LEAP model applies an organizational boundary based on operational control, consistent with the GHG Protocol Corporate Standard [7] and ISO 14064-1 principles. Only emission sources under the direct management authority of NDHU's Shoufeng Campus were included in the modeling framework. The system boundary encompasses Category 1 (direct emissions), Category 2 (indirect emissions from purchased electricity), and Category 4 (selected other indirect emissions including upstream energy and outsourced waste/wastewater treatment). Other campuses and sources outside institutional control were excluded to maintain accounting consistency.

Category 1 emissions include on-site fuel combustion, university-owned vehicle fuel use, refrigerant leakage from air-conditioning and refrigeration systems, and methane emissions from septic systems. Category 2 emissions arise from purchased grid electricity and constitute the dominant share of the campus carbon footprint. Category 4 emissions represent upstream energy-related emissions and outsourced treatment of waste and wastewater. Activity data were obtained from verified 2023 campus GHG inventory records, including electricity billing data, floor area statistics for energy use intensity (EUI) analysis, fleet fuel consumption logs, refrigerant charge and refill records, septic system maintenance data, and waste disposal reports. Where minor data gaps existed, conservative assumptions were adopted in accordance with [24] guidance and Taiwan's official emission factor database. A location-based emission factor of 0.495 kg CO₂e/kWh was applied for grid electricity in both the base year and BAU projection, consistent with the official national value announced by Taiwan's Energy Administration, Ministry of Economic Affairs [30].

2.3.2. Current Accounts (Base Year 2023)

The verified 2023 greenhouse gas inventory serves as the “Current Accounts” reference year for all scenario simulations. Total emissions for 2023 were 11,350.48 tCO₂e. Of this total, Category 1 contributed 2167.24 tCO₂e (approximately 19%), Category 2 contributed 7635.26 tCO₂e (approximately 67%), and Category 4 contributed 1547.98 tCO₂e (approximately 14%). The emissions profile is dominated by carbon dioxide, accounting for approximately 81.3% of total CO₂e, while methane (11.8%) and hydrofluorocarbons (6.9%) represent significant non-CO₂ components. Sulfur hexafluoride appears only as a minor trace gas.

Within Category 1, refrigerant leakage and septic-system methane represent the primary direct emission sources, reflecting the high global warming potential of certain cooling agents and the sanitation infrastructure configuration of the campus. Mobile combustion from the university fleet and limited stationary fuel use contribute a comparatively smaller share but remain operationally controllable. Category 2 emissions from purchased electricity constitute the principal emissions driver, highlighting the importance of electricity demand management and renewable energy integration in subsequent mitigation scenarios. Category 4 emissions reflect upstream electricity and fuel production as well as outsourced waste and wastewater treatment, indicating additional reduction opportunities through demand-side efficiency, diversion strategies, and improved resource management.

This baseline emissions structure establishes the quantitative foundation for scenario development and enables identification of priority sectors for mitigation within the LEAP modeling framework. By construction, the LEAP base-year output replicates the 2023 verified inventory totals exactly, providing an empirical grounding for all subsequent scenario projections. This calibration approach constitutes the primary form of real-world benchmarking available for the emissions modeling component. Benchmarking of InVEST-estimated carbon stocks against field-measured biomass data was not possible in this study due to the absence of campus-level biomass surveys, and is identified as a priority for future validation work in Section 6.

2.3.3. Business-As-Usual (BAU) Scenario

The Business-as-Usual (BAU) scenario represents the counterfactual trajectory in which no additional mitigation measures are implemented beyond existing operational practices. It provides the reference case against which the effectiveness of all intervention scenarios is evaluated. Under BAU, annual electricity demand is assumed to grow at 0.5%, reflecting incremental campus expansion without energy efficiency improvements. Fossil fuel-based transportation and backup generation systems remain unchanged, with no electrification of the vehicle fleet. Waste management practices and septic methane emissions are held constant at baseline levels, and no improvements in refrigerant management or leakage reduction are assumed. Although photovoltaic (PV) systems remain operational, they are treated as grid-exporting without on-site self-consumption and therefore provide no direct emission reduction under the location-based accounting approach. The grid emission factor is fixed at 0.495 kg CO₂e/kWh throughout the projection period to isolate campus-driven changes from potential external grid decarbonization. Table 4 represents the business-as-usual project emission from year 2023 to 2040.

Under these assumptions, total emissions increase gradually from 11,350.48 tCO₂e in 2023 to 12,026.10 tCO₂e in 2040, representing an overall rise of approximately 6%. As shown in Figure 5, the emissions profile remains structurally dominated by purchased electricity (Category 2), which increases from 7635.26 tCO₂e to 8310.88 tCO₂e over the period due to demand growth. In contrast, Category 1 (direct emissions) and Category 4 (selected indirect emissions) remain constant by construction of the BAU scenario. Consequently,

electricity's share of total campus emissions increases marginally from approximately 67% to nearly 69% by 2040.

Table 4. Business-as-Usual Projected Emissions (2023–2040).

Year	Cat. 1 (tCO ₂ e)	Cat. 2 (tCO ₂ e)	Cat. 4 (tCO ₂ e)	Total (tCO ₂ e)
2023	2167.24	7635.26	1547.98	11,350.48
2030	2167.24	7906.54	1547.98	11,621.76
2035	2167.24	8106.19	1547.98	11,821.41
2040	2167.24	8310.88	1547.98	12,026.10

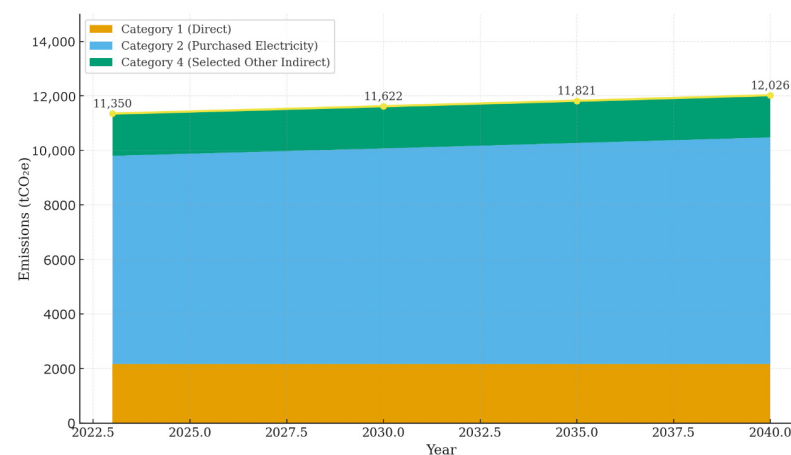


Figure 5. Business-as-Usual Emission Trajectory (2023–2040).

Figure 6 illustrates the total emissions trajectory under BAU, highlighting a smooth and incremental increase rather than structural shifts across categories. The approximately 675.6 tCO₂e rise between 2023 and 2040 is almost entirely attributable to electricity demand growth, reinforcing that without targeted intervention in electricity consumption or procurement, overall emissions remain locked into a gradually rising pathway. This conservative baseline provides a stable analytical benchmark for quantifying the relative contribution of subsequent mitigation measures, including efficiency improvements, on-site renewable deployment, electrification strategies, and non-CO₂ emission controls.

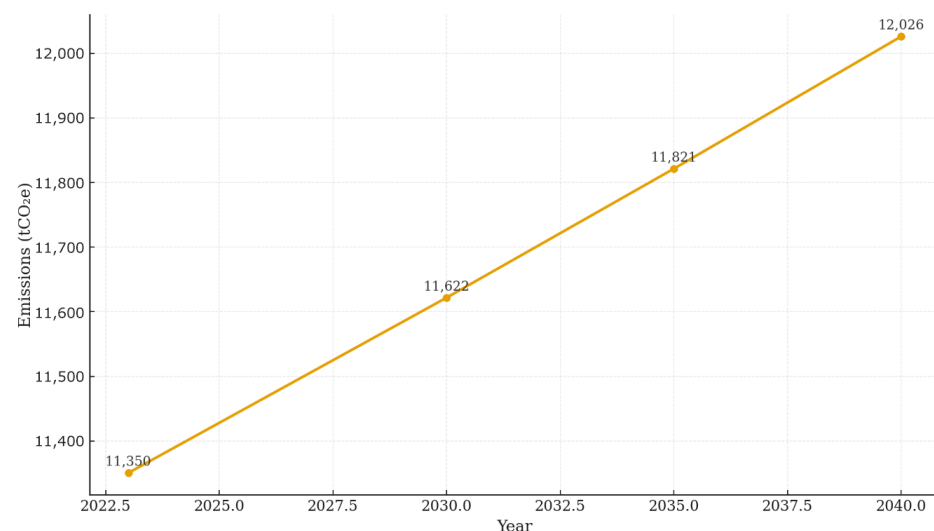


Figure 6. Business-as-Usual total emissions (2023–2040).

2.3.4. Mitigation Scenario Design

To evaluate decarbonization options, eight standalone mitigation scenarios (S1–S8) were developed within the LEAP framework, each targeting a specific emission source or structural reduction strategy. The scenarios were parameterized independently to quantify their individual impact relative to the BAU trajectory for 2030 and 2040. Because each scenario modifies different components of the emissions structure, percentage reductions are non-additive; interactions among efficiency improvements, renewable energy deployment, and procurement strategies were addressed subsequently in integrated pathway analysis.

Scenario S1 represents energy-use intensity (EUI) reduction across campus buildings and treats efficiency improvements as the foundational mitigation lever. The scenario assumes a 20% reduction in EUI by 2030 and 35% by 2040 across the majority of building floor area. When modeled independently, this reduces total emissions by approximately 11% in 2030 and nearly 20% by 2040, primarily through decreased purchased electricity (Category 2).

Scenario S2 introduces photovoltaic (PV) self-consumption, shifting solar generation from export-oriented to behind-the-meter use. The scenario assumes solar generation meets approximately 30% of annual electricity demand by 2030 and 65% by 2040. Under standalone evaluation, this displaces grid imports directly and yields an estimated 20% reduction in 2030 and up to 45% by 2040. In integrated scenarios, the effective contribution of PV depends on residual electricity demand after efficiency measures.

Scenario S3 addresses the remaining grid electricity through green power procurement using market-based instruments. The scenario assumes coverage of 50% of residual electricity in 2030 and full coverage by 2040. When assessed independently against BAU, this results in reductions of up to 34% in 2030 and approximately 69% by 2040, contingent upon the remaining grid share after S1 and S2 are applied.

Scenarios S4 through S7 target non-CO₂ and operational sources. Scenario S4 reduces refrigerant-related emissions through progressive transition to low-global-warming-potential (GWP) systems and improved leakage control, achieving approximately 4–5% reduction by 2030 and up to 10% by 2040. Scenario S5 mitigates septic methane emissions through sanitation system improvements, resulting in 3–5% reduction by 2030 and up to 7% by 2040. Scenario S6 models full fleet electrification by 2032 combined with reduced generator testing frequency; due to its small baseline share, the contribution remains modest ($\leq 2\%$ by 2040). Scenario S7 improves waste diversion and wastewater management efficiency, contributing approximately 1–3% reduction by 2040.

Scenario S8 represents nature-based carbon removal through ecosystem enhancement within the campus boundary. Based on InVEST carbon stock modeling, historical and projected LULC changes indicate an estimated increase of approximately 1140 metric tons of carbon (tC) between 2018 and 2030, equivalent to roughly 4182 tCO₂e after unit conversion. This trend, combined with planned ecosystem enhancement measures, supports the modeling assumption that annual sink capacity can scale to approximately 1000–1800 tCO₂e per year by 2040. Within LEAP, these removals are represented as negative emissions time series and applied only after operational mitigation scenarios are implemented. A permanence buffer is included to account for potential carbon reversals due to disturbance risks, ensuring conservative accounting of land-based sequestration.

2.3.5. Integrated Decarbonization Pathways

To evaluate system-level outcomes, the standalone scenarios were combined into two integrated decarbonization pathways reflecting different strategic emphases. Pathway A represents a balanced portfolio approach combining moderate efficiency improvements, substantial PV self-consumption, full green power coverage of residual electricity by 2040,

comprehensive non-CO₂ controls, and deployment of campus-based carbon sinks. Pathway B emphasizes deeper on-site mitigation through higher EUI and PV targets with reduced reliance on green power procurement, resulting in a small residual emission gap by 2040 that can be addressed through expanded sink capacity.

Both pathways were evaluated annually for gross emissions, post-sink net emissions, percentage reduction relative to BAU, and contribution of individual mitigation levers. Results indicate that both pathways achieve greater than 95% reduction relative to BAU by 2040, with Pathway A reaching full net-zero under modeled assumptions.

2.4. Integrated LEAP–InVEST Carbon Accounting Framework

To ensure consistency between operational emissions and ecosystem-based carbon sequestration, this study establishes an integrated accounting framework that reconciles emission flows and carbon stock changes within a unified analytical structure. The framework explicitly links LEAP-based emissions projections with InVEST-derived carbon storage dynamics, enabling the calculation of net emissions under an MRV-aligned system.

At the core of the framework is the temporal alignment between annual greenhouse gas emissions (flow variables) and changes in terrestrial carbon storage (stock variables). Operational emissions are modeled annually using LEAP and expressed in metric tons of carbon dioxide equivalent (tCO₂e). In contrast, the InVEST model estimates carbon storage in metric tons of carbon (tC), which is subsequently converted into tCO₂e using the molecular conversion factor (3.667). Carbon removals are derived from the annual change in carbon stock rather than absolute stock values, ensuring compatibility with emissions accounting. The integrated accounting relationship is defined as follows:

$$NetEmissions_t = GrossEmissions_t - Removals_t$$

where

NetEmissions_t represents net greenhouse gas emissions in year *t* (tCO₂e);

GrossEmissions_t represents total operational emissions derived from LEAP (tCO₂e);

Removals_t represents carbon sequestration derived from ecosystem changes (tCO₂e).

Carbon removals are calculated based on temporal changes in carbon stocks:

$$Removals_t = (CarbonStock_t - CarbonStock_{t-1}) \times 3.667$$

This formulation ensures that only incremental carbon sequestration is credited, thereby avoiding double counting associated with static carbon stock estimates. The framework also maintains strict boundary consistency by aligning spatial boundaries (campus extent) and organizational boundaries (operational control) across both modeling systems.

To further enhance accounting robustness, three key principles are applied. First, boundary consistency is maintained to ensure that emissions and removals are evaluated within the same institutional domain. Second, temporal consistency is achieved by converting stock changes into annual flows, allowing direct comparison with emissions trajectories. Third, MRV alignment is enforced through transparent separation of gross emissions, removals, and residual emissions, enabling traceable and verifiable net-zero assessments.

Within this integrated structure, mitigation measures are applied sequentially. Demand-side efficiency and supply-side decarbonization measures (LEAP scenarios) are implemented first to reduce gross emissions, followed by the application of ecosystem-based removals (InVEST-derived) to offset residual emissions. This hierarchical structure reflects best practice in net-zero planning, prioritizing emissions reduction before reliance on carbon sequestration.

The framework shown in Figure 7 integrates operational emissions modeling (LEAP) and spatial carbon storage assessment (InVEST) within a unified accounting structure. Gross emissions are estimated through scenario-based energy modeling, while carbon removals are derived from changes in ecosystem carbon stocks. These components are reconciled through an MRV-aligned integration module that ensures boundary consistency, flow–stock alignment, and avoidance of double counting. The framework follows a hierarchical mitigation logic in which emissions reduction and decarbonization measures precede the application of nature-based removals to achieve net-zero emissions.

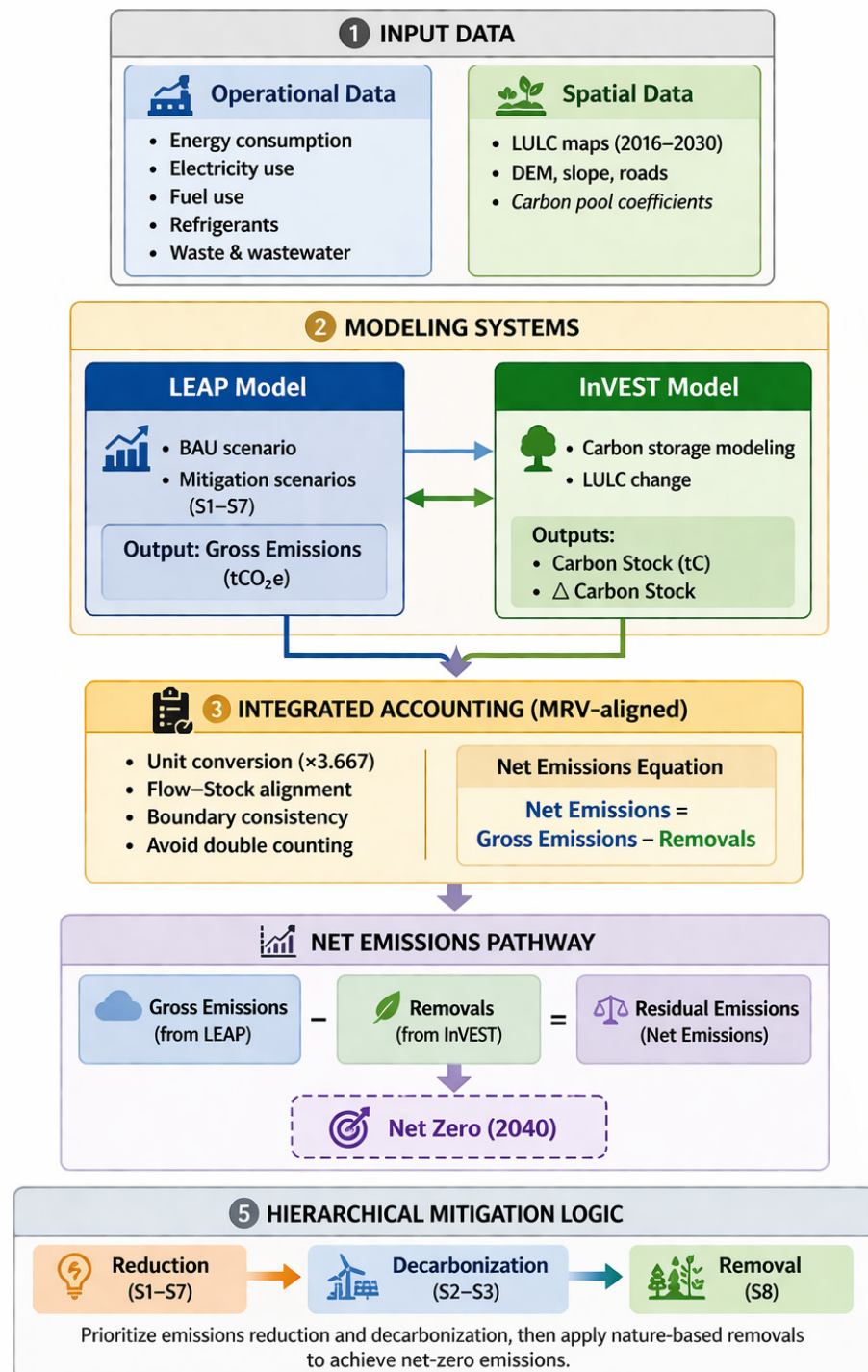


Figure 7. Integrated LEAP–InVEST framework for MRV-aligned campus carbon neutrality.

3. Results

The combined application of the InVEST and LEAP models enables a quantitative assessment of both terrestrial carbon storage dynamics and operational greenhouse gas emissions within the NDHU Shoufeng Campus boundary. By linking land-based carbon stock changes with scenario-based emissions projections, the analysis provides a unified perspective on gross emissions, ecosystem removals, and net emissions trajectories under alternative decarbonization strategies.

3.1. InVEST Model Results: Carbon Storage and Sequestration Dynamics

The InVEST Carbon Storage and Sequestration model was applied to quantify spatial and temporal changes in terrestrial carbon stocks within the campus boundary from 2018 to 2030. Carbon storage estimates were derived from multi-temporal LULC datasets combined with standardized carbon pool coefficients for aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter. The results provide an empirical basis for evaluating the magnitude and variability of campus-based carbon sinks and for assessing their contribution relative to projected operational emissions.

3.1.1. Total Carbon Stock (2018–2024)

Carbon storage was estimated for four observation years (2018, 2020, 2022, and 2024) using Sentinel-2-derived LULC maps. Total carbon stocks were calculated in metric tons of carbon (tC) and converted to metric tons of CO₂ equivalent (tCO₂e) using the molecular conversion factor of 3.667. As summarized in Table 5, total carbon storage increased between 2018 and 2020, followed by a slight decline in 2022 and a subsequent recovery in 2024. Across the full period, the campus exhibited a net increase of approximately 1164.1 tC, equivalent to 4268.9 tCO₂e.

Table 5. Total Carbon Storage from 2018 to 2024.

Year	Carbon Storage (tC)	Carbon Storage (tCO ₂ e)
2018	10,078.60	36,958.23
2020	11,464.46	42,040.17
2022	10,997.42	40,327.54
2024	11,242.74	41,227.13

These temporal variations correspond to observed changes in land cover distribution, particularly shifts among vegetated, agricultural, and built-up classes documented in Section 2.2.1. The overall positive net change indicates that, over the study period, the campus landscape functioned as a net carbon sink. However, the magnitude of annual change remains modest relative to operational emissions levels, highlighting the need to evaluate sequestration contributions within the broader context of energy-related emissions reduction.

3.1.2. Projected Carbon Sequestration (2026 and 2030)

Future land use and land cover conditions were simulated for 2026 and 2030 using MOLUSCE-based transition modeling, incorporating spatial drivers including elevation, slope, and proximity to road infrastructure. The projected LULC maps were used as inputs to the InVEST sequestration mode to estimate net carbon stock changes relative to 2024 conditions. The projected total carbon storage is listed in Table 6.

Table 6. Projected Total Carbon Storage.

Year	Carbon Storage (tC)	Carbon Storage (tCO ₂ e)	Δ from Previous Year (tCO ₂ e)	% Change
2024	11,242.74	41,227.13	–	–
2026	11,111.74	40,746.75	–480.38	–1.17%
2030	11,218.68	41,218.68	471.93	1.16%

Model results indicate a short-term decline in carbon stock between 2024 and 2026 (–1.17%), followed by a partial recovery by 2030 (+1.16%). These fluctuations reflect shifts among vegetated and built-up land classes documented in the LULC projections. Importantly, total carbon storage in 2030 approaches the 2024 level, indicating relative stability of aggregate campus carbon stocks over the medium term. The magnitude of change remains modest compared to operational emissions, reinforcing the importance of evaluating sequestration within an integrated emissions-reduction framework.

3.1.3. Contribution of Land Cover Types to Carbon Storage

Carbon stock distribution analysis demonstrates that tree-covered areas consistently account for most of the terrestrial carbon storage due to their higher biomass and associated soil carbon pools. Rangelands and croplands contribute moderate levels of storage, depending on vegetation density and management practices. In contrast, built-up areas contribute minimally because of limited biomass and soil disturbance, while water bodies and bare ground have negligible carbon values under the applied coefficient assumptions.

Spatial analysis reveals that carbon density is concentrated primarily in forested and vegetated zones, particularly in the southeastern and central portions of the campus. These areas therefore represent the principal contributors to total carbon storage within the institutional boundary. The spatial heterogeneity observed across LULC classes underscores the sensitivity of campus carbon stocks to land conversion patterns.

3.1.4. Carbon Sequestration Rate Estimation and Modeling Implications

To derive an empirical sequestration baseline for integration into the emissions modeling framework, annual carbon removal rates were estimated by combining the observed historical carbon stocks from Table 5 with the projected values from Table 6. Total campus carbon storage increased from 36,958.23 tCO₂e in 2018 to a projected 41,218.68 tCO₂e in 2030, representing a net gain of approximately 4260 tCO₂e over twelve years. Dividing this net change by the number of years yields a simple average annual sequestration rate of approximately 355 tCO₂e per year, which is conservatively adopted as 350 tCO₂e per year for subsequent modeling purposes.

It should be noted that this average reflects the net outcome of a dynamic land-cover system rather than a uniform annual rate. The year-by-year carbon stock changes across the study period show alternating phases of gain and decline, corresponding to land-cover transitions documented in the LULC analysis, including periods of vegetation disturbance, infrastructure development, and subsequent ecological recovery within the campus boundary. Despite this inherent variability, the overall twelve-year trend remains consistently positive, confirming that the campus landscape functions as a net carbon sink under existing land management conditions. The simple average of approximately 350 tCO₂e per year therefore represents a conservative long-run central estimate of campus sequestration capacity under baseline land management rather than a precise guaranteed annual value.

This derived baseline rate serves as the empirical lower bound for nature-based removal modeling in the integrated pathway analysis presented in Section 3.2. As discussed in that section, planned ecosystem enhancement measures and the availability of underuti-

lized vegetated land within the campus boundary provide the basis for projecting removal capacity beyond this conservative baseline in future projection years.

3.2. LEAP Model Results: Mitigation Scenarios and Carbon Neutrality Pathways

The LEAP model was used to simulate the effects of individual mitigation scenarios and integrated decarbonization pathways for the NDHU Shoufeng Campus through 2040. Results are presented relative to the Business-as-Usual (BAU) trajectory, allowing direct comparison of percentage and absolute emission reductions. Standalone scenario performance (S1–S8) is first evaluated, followed by integrated pathway outcomes that combine multiple mitigation measures and incorporate carbon sink contributions derived from InVEST.

3.2.1. Scenario S1—Energy-Use Intensity (EUI) Reduction

Scenario S1 models demand-side efficiency improvements through reductions in building energy-use intensity (EUI), assuming a 20% decrease by 2030 and 35% by 2040 across the majority of campus floor area. Because purchased electricity accounts for the largest share of total emissions, reductions occur primarily within Category 2.

When evaluated independently against BAU, total emissions decline by 10.9% in 2030, 16.5% in 2035, and 19.4% in 2040. In absolute terms, emissions decrease from 11,621.76 tCO₂e to 10,356.71 tCO₂e in 2030, from 11,821.41 tCO₂e to 9875.92 tCO₂e in 2035, and from 12,026.10 tCO₂e to 9699.05 tCO₂e in 2040 (Table 7; Figure 8). These reductions correspond to approximately 1265 tCO₂e avoided in 2030 and 2327 tCO₂e avoided in 2040 relative to BAU.

Table 7. Scenario S1 (EUI reduction) vs. BAU.

Year	BAU Total (tCO ₂ e)	Cat. 2 Share of Total (%)	S1 Reduction vs. BAU (%)	S1 Reduction (tCO ₂ e)	S1 Total (tCO ₂ e)
2023	11,350.48	67.27	0	0	11,350.48
2030	11,621.76	68.03	10.89	1265.05	10,356.71
2035	11,821.41	68.57	16.46	1945.49	9875.92
2040	12,026.10	69.11	19.35	2327.05	9699.05

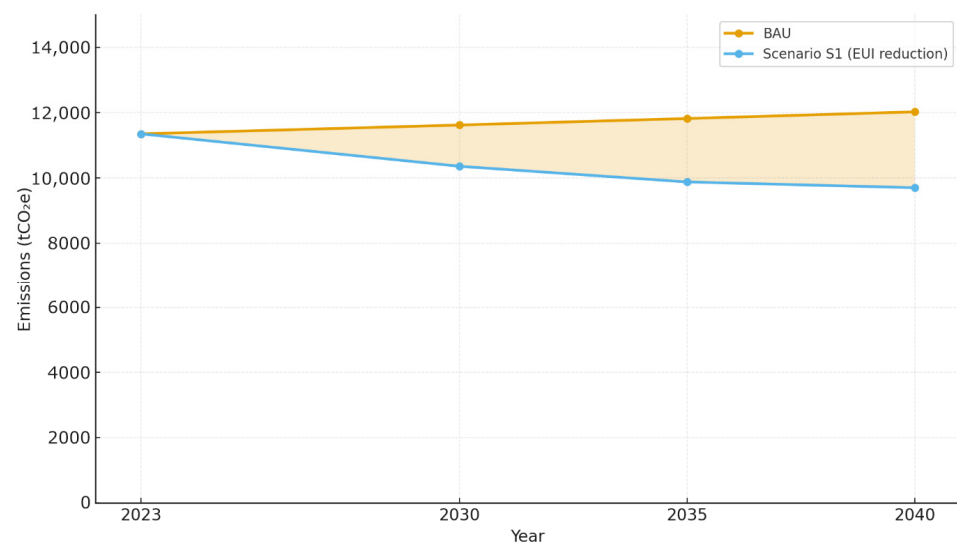


Figure 8. Scenario S1 vs. BAU—Shaded Reduction (2023–2040).

The results confirm that demand-side efficiency represents a structurally significant mitigation lever within the campus emissions profile. By lowering electricity consumption before supply-side interventions are applied, Scenario S1 reduces the residual demand that must be addressed through photovoltaic self-consumption or green power procurement

in subsequent scenarios. Interaction effects are accounted for in the integrated pathway analysis to avoid double counting of reductions.

3.2.2. Scenario S2—Photovoltaic (PV) Self-Consumption

Scenario S2 evaluates the effect of shifting campus photovoltaic generation from export-oriented operation to behind-the-meter self-consumption. Under this configuration, on-site solar generation directly offsets purchased grid electricity on a one-to-one basis within the location-based accounting framework. The standalone scenario assumes that self-consumed PV supplies 30% of annual electricity demand by 2030, 50% by 2035, and 65% by 2040.

When modeled independently against the BAU trajectory, reductions occur entirely within Category 2 (purchased electricity). Total emissions decline by approximately 20.41% in 2030, 34.29% in 2035, and 44.92% in 2040 relative to BAU. In absolute terms, emissions decrease from 11,621.76 tCO₂e to 9249.80 tCO₂e in 2030, from 11,821.41 tCO₂e to 7768.32 tCO₂e in 2035, and from 12,026.10 tCO₂e to 6624.03 tCO₂e in 2040 (Table 8; Figure 9).

Table 8. Scenario S2 (PV self-consumption) vs. BAU.

Year	BAU Total (tCO ₂ e)	Cat. 2 Share of Total (%)	PV Self-Use Share of Electricity (%)	S2 Reduction vs. BAU (%)	S2 Reduction (tCO ₂ e)	S2 Total (tCO ₂ e)
2023	11,350.48	67.27	0	0	0	11,350.48
2030	11,621.76	68.03	30	20.41	2371.96	9249.80
2035	11,821.41	68.57	50	34.29	4053.10	7768.32
2040	12,026.10	69.11	65	44.92	5402.07	6624.03

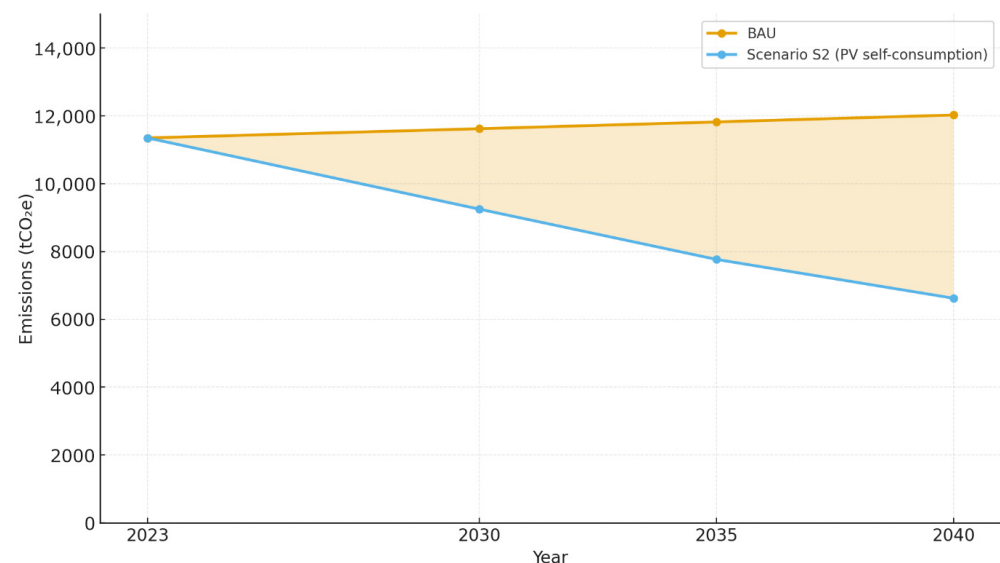


Figure 9. Scenario S2 vs. BAU—Shaded Reduction (2023–2040).

These results indicate that supply-side decarbonization through on-site renewable generation produces larger reductions than demand-side efficiency when evaluated independently, reflecting the structural dominance of electricity in the campus emissions profile. In integrated pathway modeling, the effective contribution of PV self-consumption depends on residual electricity demand after efficiency measures are applied; interaction effects are explicitly accounted for to prevent double counting of reductions.

3.2.3. Scenario S3—Green Power Procurement (Market-Based Scope 2)

Scenario S3 evaluates the effect of procuring certified renewable electricity through market-based instruments such as power purchase agreements (PPAs), green tariffs, or

renewable energy certificates (RECs). Under market-based accounting, the procured share of electricity is assigned a zero or contract-specific emission factor, while location-based emissions remain disclosed for transparency. The standalone scenario assumes procurement of 50% of grid electricity by 2030, 75% by 2035, and 100% by 2040.

When modeled independently against BAU, reductions occur entirely within Category 2 emissions and scale proportionally with the procurement share. Total emissions decline by approximately 34.02% in 2030, 51.43% in 2035, and 69.11% in 2040 relative to BAU. In absolute terms, emissions decrease from 11,621.76 tCO₂e to 7668.49 tCO₂e in 2030, from 11,821.41 tCO₂e to 5741.77 tCO₂e in 2035, and from 12,026.10 tCO₂e to 3715.22 tCO₂e in 2040 (Table 9; Figure 10).

Table 9. Scenario S3 (Green power procurement) vs. BAU.

Year	BAU Total (tCO ₂ e)	Cat. 2 Share of Total (%)	Green Power Share of Grid (%)	S3 Reduction vs. BAU (%)	S3 Reduction (tCO ₂ e)	S3 Total (tCO ₂ e)
2023	11,350.48	67.27	0	0	0	11,350.48
2030	11,621.76	68.03	50	34.02	3953.27	7668.49
2035	11,821.41	68.57	75	51.43	6079.64	5741.77
2040	12,026.10	69.11	100	69.11	8310.88	3715.22

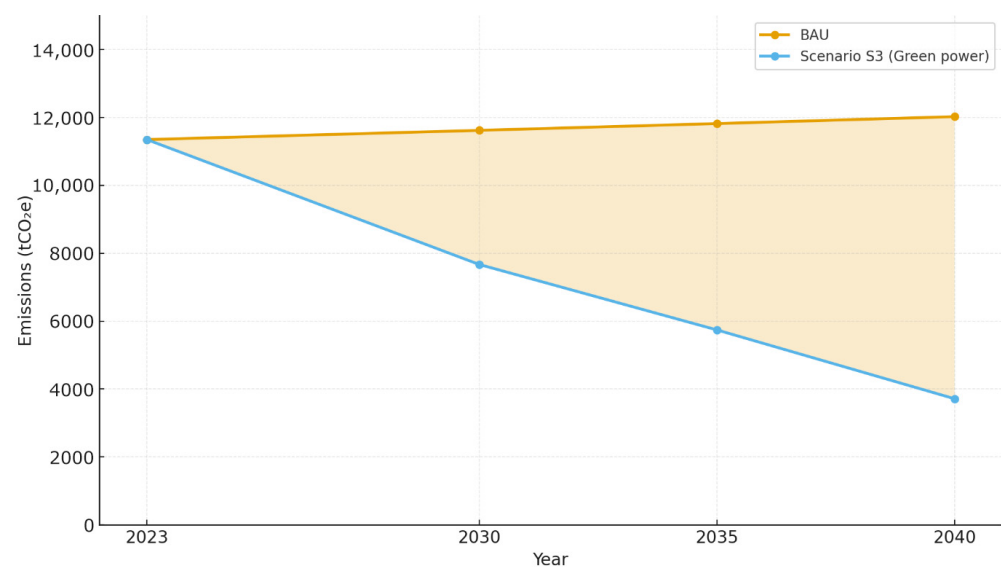


Figure 10. Scenario S3 vs. BAU—Shaded reduction (2023–2040).

These results indicate that contractual decarbonization of electricity provides the largest single reduction potential among standalone scenarios, reflecting the dominant contribution of purchased electricity to total campus emissions. In integrated pathway analysis, green power procurement is applied after demand-side efficiency and on-site renewable generation, ensuring that procurement volumes reflect residual electricity demand and that reductions are not double counted.

3.2.4. Scenario S4—Refrigerant Management and Low-GWP Transition

Scenario S4 addresses hydrofluorocarbon (HFC) emissions from campus cooling systems through a combination of leakage reduction and transition to low-global-warming-potential (GWP) refrigerants. In the base year, HFCs account for approximately 6.88% of total campus emissions. The standalone scenario assumes progressive reduction in leakage rates and phased replacement of high-GWP systems, resulting in elimination of approximately 60% of HFC emissions by 2030, 85% by 2035, and 95% by 2040.

Because these reductions apply to the HFC share of total emissions, the overall campus impact corresponds to a 4.13% reduction relative to BAU in 2030, 5.85% in 2035, and 6.54% in 2040. In absolute terms, this represents approximately 480 tCO₂e avoided in 2030, 691 tCO₂e in 2035, and 786 tCO₂e in 2040 (Table 10; Figure 11).

Table 10. Scenario S4 (Refrigerants) vs. BAU.

Year	BAU Total (tCO ₂ e)	Assumed HFC Share of Total (%)	Reduction in HFC Emissions (%)	S4 Reduction vs. BAU (%)	S4 Reduction (tCO ₂ e)	S4 Total (tCO ₂ e)
2023	11,350.48	6.88	0	0	0	11,350.48
2030	11,621.76	6.88	60	4.13	479.75	11,142.01
2035	11,821.41	6.88	85	5.85	691.32	11,130.09
2040	12,026.10	6.88	95	6.54	786.03	11,240.07

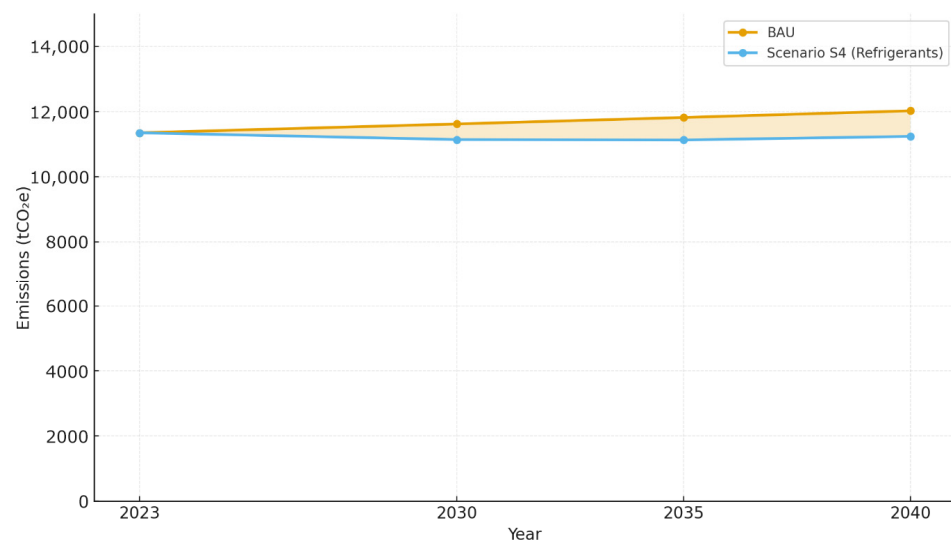


Figure 11. Scenario S4 vs. BAU—Shaded reduction (2023–2040).

Although smaller in magnitude than electricity-focused scenarios, refrigerant management provides structurally important reductions from non-electric sources. Because these emissions occur outside the electricity category, the reductions stack independently with efficiency, photovoltaic, and green-power scenarios in integrated pathway modeling without overlap.

3.2.5. Scenario S5—Septic Methane Abatement

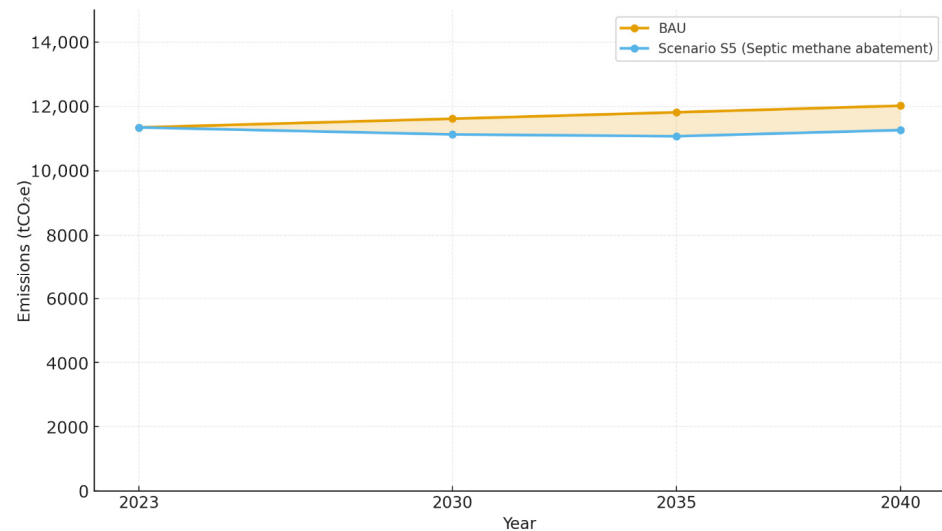
Scenario S5 addresses methane (CH₄) emissions associated with on-campus septic systems. Methane represents a high-global-warming-potential gas, and in the base year septic-related methane is modeled as contributing approximately 7% of total campus emissions. The standalone scenario assumes progressive upgrading of septic systems, with approximately 60% of septic load transitioned or abated by 2030 and 90% by 2035, with sustained performance through 2040.

Under these assumptions, whole-campus emissions decline by approximately 4.2% relative to BAU in 2030 and 6.3% in 2035 and 2040. In absolute terms, total emissions decrease from 11,621.76 tCO₂e to 11,133.65 tCO₂e in 2030, from 11,821.41 tCO₂e to 11,076.66 tCO₂e in 2035, and from 12,026.10 tCO₂e to 11,268.46 tCO₂e in 2040 (Table 11; Figure 12).

Although smaller than electricity-focused measures, septic methane abatement provides structurally important reductions from non-electric sources. Because these emissions occur outside Category 2, reductions from Scenario S5 stack independently with electricity, refrigerant, and renewable-energy scenarios in integrated pathway modeling.

Table 11. Scenario S5 (Septic methane abatement) vs. BAU.

Year	BAU Total (tCO ₂ e)	Assumed Septic Share of Total (%)	Abatement of Septic Emissions (%)	S5 Reduction vs. BAU (%)	S5 Reduction (tCO ₂ e)	S5 Total (tCO ₂ e)
2023	11,350.48	7	0	0	0	11,350.48
2030	11,621.76	7	60	4.2	488.11	11,133.65
2035	11,821.41	7	90	6.3	744.75	11,076.66
2040	12,026.10	7	90	6.3	757.64	11,268.46

**Figure 12.** Scenario S5 vs. BAU—Shaded reduction (2023–2040).

3.2.6. Scenario S6—Fleet Electrification and Generator Reform

Scenario S6 addresses fuel combustion from the campus vehicle fleet and diesel consumption associated with periodic generator testing. In the BAU trajectory, these sources collectively account for approximately 2% of total emissions. The standalone scenario assumes approximately 40% abatement by 2030 through partial fleet electrification and reduced generator test operation, increasing to roughly 90% abatement by 2035 and sustained through 2040.

Under these assumptions, whole-campus emissions decline by approximately 0.8% relative to BAU in 2030 and 1.8% in 2035–2040. In absolute terms, emissions decrease from 11,621.76 tCO₂e to 11,528.79 tCO₂e in 2030 (≈ 93 tCO₂e avoided), from 11,821.41 tCO₂e to 11,608.62 tCO₂e in 2035 (≈ 213 tCO₂e avoided), and from 12,026.10 tCO₂e to 11,809.63 tCO₂e in 2040 (≈ 216 tCO₂e avoided) (Table 12; Figure 13).

Table 12. Scenario S6 (Fleet electrification & generator testing reform) vs. BAU.

Year	BAU Total (tCO ₂ e)	Assumed Mobile + Generator Share of Total (%)	Abatement of Mobile + Generator Emissions (%)	S6 Reduction vs. BAU (%)	S6 Reduction (tCO ₂ e)	S6 Total (tCO ₂ e)
2023	11,350.48	2	0	0	0	11,350.48
2030	11,621.76	2	40	0.8	92.97	11,528.79
2035	11,821.41	2	90	1.8	212.79	11,608.62
2040	12,026.10	2	90	1.8	216.47	11,809.63

Although relatively small in magnitude compared with electricity-related measures, Scenario S6 provides durable reductions from fully controllable sources. Because these emissions occur outside the electricity and refrigerant categories, reductions stack independently within integrated pathway modeling without interaction effects.

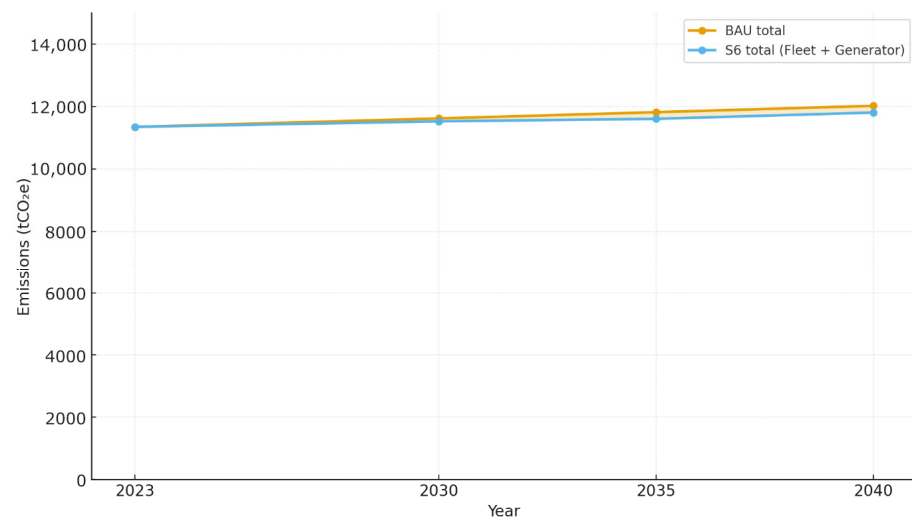


Figure 13. Scenario S6 vs. BAU—Shaded reduction (2023–2040).

3.2.7. Scenario S7—Waste and Wastewater Optimization

Scenario S7 targets emissions associated with solid waste management and wastewater treatment processes. In the BAU trajectory, waste and wastewater-related emissions are modeled as contributing approximately 3% of total campus emissions. The standalone scenario assumes progressive improvement in material diversion, food-waste separation, and wastewater process optimization, resulting in approximately 55% abatement of these emissions by 2030, 65% by 2035, and 70% by 2040.

Under these assumptions, whole-campus emissions decline by approximately 1.65% relative to BAU in 2030, 1.95% in 2035, and 2.10% in 2040. In absolute terms, emissions decrease from 11,621.76 tCO₂e to 11,430.00 tCO₂e in 2030, from 11,821.41 tCO₂e to 11,590.89 tCO₂e in 2035, and from 12,026.10 tCO₂e to 11,773.55 tCO₂e in 2040 (Table 13; Figure 14).

Table 13. Scenario S7 (Waste & wastewater optimization) vs. BAU.

Year	BAU Total (tCO ₂ e)	Assumed Waste + Wastewater Share of Total (%)	Abatement of Waste + Wastewater Emissions (%)	S7 Reduction vs. BAU (%)	S7 Reduction (tCO ₂ e)	S7 Total (tCO ₂ e)
2023	11,350.48	3	0	0	0	11,350.48
2030	11,621.76	3	55	1.65	191.76	11,430.00
2035	11,821.41	3	65	1.95	230.52	11,590.89
2040	12,026.10	3	70	2.1	252.55	11,773.55

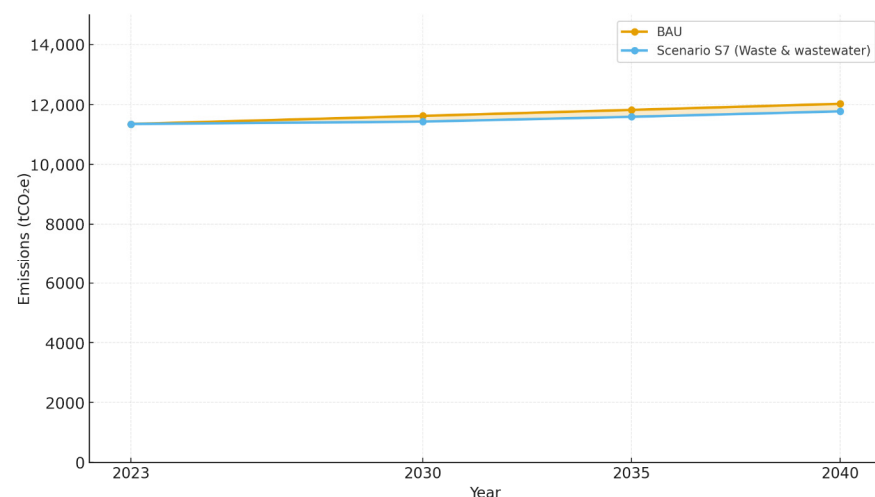


Figure 14. Scenario S7 vs. BAU—Shaded reduction (2023–2040).

Although modest in magnitude compared with electricity-related measures, Scenario S7 reduces methane and nitrous oxide emissions from non-electric sources. These reductions stack independently with energy, refrigerant, and fleet scenarios in integrated pathway modeling and contribute to minimizing the residual emissions that must be offset through carbon removals.

3.2.8. Scenario S8—Campus Carbon Sinks (Nature-Based Removals)

Scenario S8 incorporates negative emissions from campus-based nature-based solutions, including tree and forest enrichment (green carbon), soil carbon enhancement (yellow carbon), and freshwater blue-green systems (blue carbon). These removals are modeled as annual net sequestration values within LEAP and are grounded in the spatial carbon stock estimates derived from the InVEST analysis presented in Section 3.1.4. As established in that section, the empirical baseline annual sequestration rate under existing land management conditions is approximately 350 tCO₂e per year, derived from a net campus carbon stock increase of approximately 4260 tCO₂e over the 2018–2030 period. This value serves as the conservative lower bound for modeling future sink capacity.

The standalone scenario assumes progressive expansion of sink capacity to approximately 900 tCO₂e per year by 2030, 1400 tCO₂e per year by 2035, and 1800 tCO₂e per year by 2040 within the campus boundary. This scaling beyond the observed baseline reflects a policy-informed scenario assumption grounded in three considerations. First, the consistently positive net carbon trend over the full 2018–2030 period confirms that the campus landscape functions as a net sink under existing conditions, establishing the directional validity of continued and enhanced sequestration. Second, the scaled values are consistent with area-based biomass accumulation rates documented for subtropical secondary forests and managed vegetation in humid climates of eastern Taiwan, where broadleaf secondary growth typically accumulates between 3 and 8 tC per hectare per year under active management conditions [24]. Third, spatial analysis of the campus LULC data identifies underutilized vegetated areas in the southeastern and peripheral zones that remain available for active ecosystem enhancement, providing realistic spatial scope for increasing removal capacity beyond the passive baseline trend.

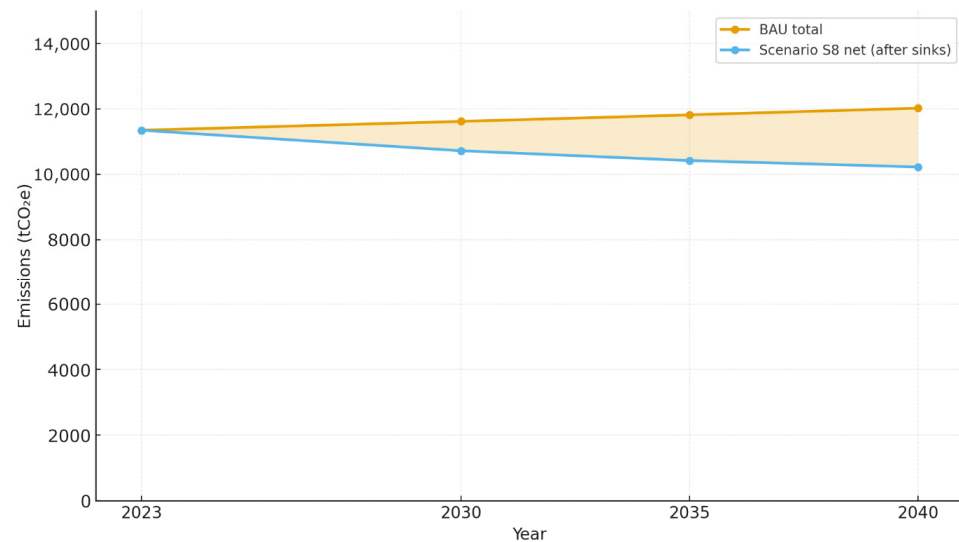
It should be noted that the 2030 sink value of 900 tCO₂e per year is grounded in empirically derived InVEST carbon stock changes across the 2018–2030 period. In contrast, the sink values for 2035 (1400 tCO₂e/yr) and 2040 (1800 tCO₂e/yr) extend beyond the InVEST modeling horizon and represent bounded scenario assumptions informed by IPCC Tier 1 biomass accumulation rates for subtropical secondary forests rather than direct model outputs. These post-2030 values therefore carry greater parametric uncertainty and should be interpreted as planning targets rather than predictive estimates.

To maintain conservative and transparent accounting, a 10% permanence buffer is applied to all modeled sink values throughout the integrated pathway analysis. This buffer reflects standard practice in verified carbon accounting frameworks, where a portion of projected biological removals is withheld to account for the risk of reversal due to disturbances such as typhoons, drought, pest outbreaks, or unplanned land-use change—all of which are relevant to the Hualien subtropical environment. The permanence buffer ensures that credited removals remain conservative and do not overstate net-zero outcomes within the MRV-aligned accounting structure adopted in this study.

When applied to BAU emissions, Scenario S8 reduces net emissions by approximately 7.7% in 2030, 11.8% in 2035, and 15.0% in 2040. In absolute terms, net totals decline from 11,621.76 tCO₂e to 10,721.76 tCO₂e in 2030, from 11,821.41 tCO₂e to 10,421.41 tCO₂e in 2035, and from 12,026.10 tCO₂e to 10,226.10 tCO₂e in 2040 (Table 14; Figure 15).

Table 14. Scenario S8 (Carbon sinks) vs. BAU.

Year	BAU Total (tCO ₂ e)	Annual Sink (tCO ₂ e)	S8 Reduction vs. BAU (%)	S8 Net Total (tCO ₂ e)
2023	11,350.48	0	0	11,350.48
2030	11,621.76	900	7.74	10,721.76
2035	11,821.41	1400	11.84	10,421.41
2040	12,026.10	1800	14.97	10,226.10

**Figure 15.** Scenario S8 vs. BAU—Shaded reduction (2023–2040).

Unlike Scenarios S1–S7, which reduce gross emissions, Scenario S8 offsets residual emissions after mitigation measures are applied. Within the integrated pathways, sequestration is sized to neutralize the remaining hard-to-abate emissions in 2040. The conservative treatment of baseline conditions and inclusion of a buffer ensure that modeled removals remain transparent and do not overstate net-zero outcomes.

3.2.9. Integrated Pathways to 2040 for Carbon Neutrality

Two integrated decarbonization pathways were constructed by combining Scenarios S1–S8 under market-based Scope 2 accounting, while BAU remains presented on a location-based basis for comparison. The pathways differ in the relative balance between demand-side efficiency, on-site renewable generation, green power procurement, non-CO₂ controls, and nature-based removals. Milestone outcomes are evaluated for 2030, 2035, and 2040.

Pathway A—Balanced Portfolio with Full Green Power by 2040

Pathway A integrates moderate energy-use intensity reduction, progressive photovoltaic self-consumption, and full coverage of residual grid electricity through certified renewable procurement by 2040. Non-CO₂ mitigation measures (refrigerant transition, septic methane abatement, waste optimization, and fleet electrification) are implemented according to the standalone scenario trajectories, while campus carbon sinks scale to approximately 1800 tCO₂e per year by 2040.

Under these combined assumptions, total market-based emissions before application of sinks decline to 4787 tCO₂e in 2030 and 2606 tCO₂e in 2035, reaching 1703 tCO₂e in 2040. After accounting for modeled carbon removals, net emissions decrease to 3887 tCO₂e in 2030 (approximately 66.6% reduction relative to BAU), 1206 tCO₂e in 2035 (approximately 89.8% reduction), and 0 tCO₂e in 2040, achieving net-zero under the modeled parameters.

Table 15 summarizes annual gross and net emissions values, while Figure 16 illustrates the trajectory relative to BAU. Figure further decomposes the 2040 reduction contributions by category, highlighting the dominant role of electricity decarbonization measures, supplemented by non-CO₂ controls and carbon sink offsets in closing the residual gap.

Table 15. Pathway A—milestones (tCO₂e).

Year	BAU Total	Pathway Total Before Sinks	Sinks	Net Total (tCO ₂ e)
2023	11,350.48	11,350.48	0	11,350.48
2030	11,621.76	4787.15	900	3887.15
2035	11,821.41	2605.94	1400	1205.94
2040	12,026.10	1702.53	1800	0

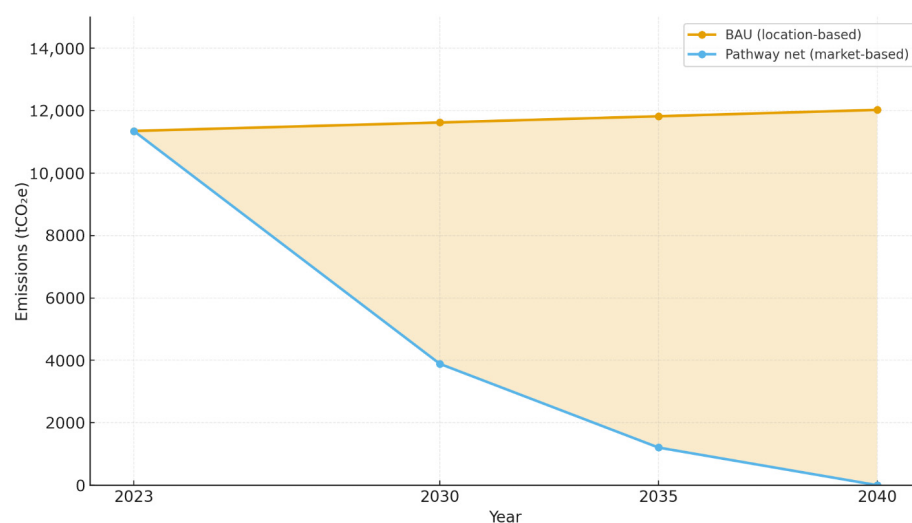


Figure 16. Pathway A vs. BAU—Net Emission (2023–2040).

Pathway B—Renewables-Leaning Strategy with Reduced Green Procurement

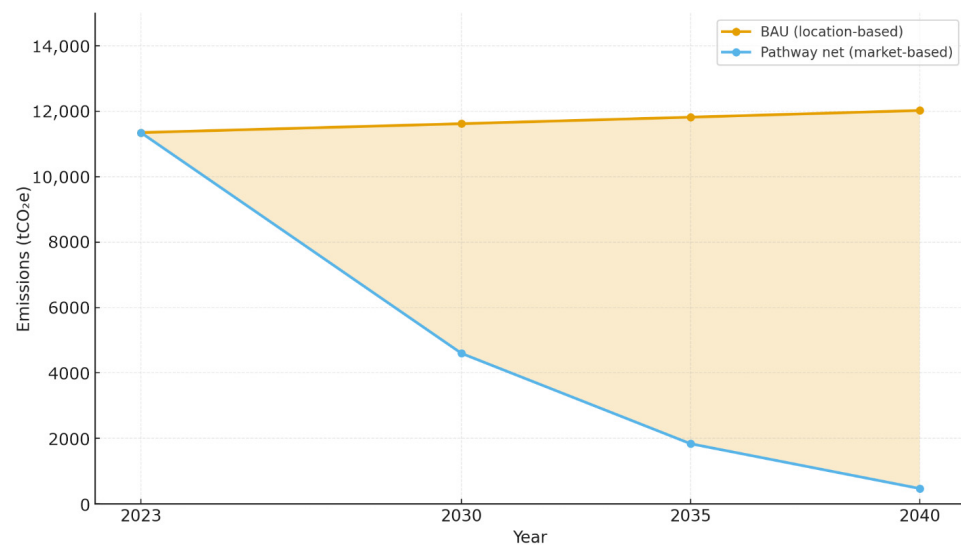
Pathway B emphasizes deeper on-site mitigation through more aggressive efficiency improvements and higher photovoltaic self-consumption, while reducing reliance on market-based green power procurement relative to Pathway A. Energy-use intensity reductions and PV deployment exceed those in Pathway A, whereas green-power procurement covers a smaller share of residual grid electricity by 2040. Non-CO₂ mitigation measures and the carbon sink scaling trajectory follow the same assumptions applied in Pathway A.

Under these parameters, total market-based emissions before application of sinks decline to 5498.74 tCO₂e in 2030 and 3236.60 tCO₂e in 2035, reaching 2267.67 tCO₂e in 2040. After accounting for modeled carbon removals, net emissions decrease to 4599 tCO₂e in 2030 (approximately 60.4% reduction relative to BAU), 1837 tCO₂e in 2035 (approximately 84.5% reduction), and 468 tCO₂e in 2040 (approximately 96.1% reduction).

The remaining 2040 residual reflects the reduced level of green-power procurement compared with Pathway A. As shown in Table 16 and Figure 17, full net-zero under this pathway would require either additional certified renewable procurement or expanded verified carbon removals beyond the baseline sink ramp. The results demonstrate that deeper on-site mitigation can substantially reduce dependence on contractual decarbonization, though a small residual persists under the modeled assumptions.

Table 16. Pathway B—milestones (tCO₂e).

Year	BAU Total	Pathway Total Before Sinks	Sinks	Net Total
2023	11,350.48	11,350.48	0	11,350.48
2030	11,621.76	5498.74	900	4598.74
2035	11,821.41	3236.60	1400	1836.60
2040	12,026.10	2267.67	1800	467.67

**Figure 17.** Pathway B vs. BAU—Net Emission (2023–2040).

3.2.10. Comparative Summary of Integrated Pathways

A direct comparison of net emissions trajectories indicates that both pathways achieve substantial decarbonization by 2035 and converge toward carbon neutrality by 2040 under the defined accounting boundary. Pathway A reaches net-zero in 2040 through full green-power coverage of residual grid electricity combined with approximately 1800 tCO₂e per year of verified campus carbon sinks. In contrast, Pathway B results in a residual of approximately 468 tCO₂e in 2040 under the same sink ramp, reflecting its lower reliance on market-based renewable procurement. Closing this residual would require either incremental expansion of verified sink capacity (on the order of ~500 tCO₂e per year) or additional green-power coverage beyond the modeled level. Comparative milestone values are summarized in Table 17.

Table 17. Net emissions comparison (tCO₂e).

Year	BAU Total	Pathway A (Net)	Pathway B (Net)
2023	11,350.48	11,350.48	11,350.48
2030	11,621.76	3887.15	4598.74
2035	11,821.41	1205.94	1836.60
2040	12,026.10	0	467.67

Across both pathways, reductions are structurally dominated by electricity-related measures, including energy-use intensity reduction, photovoltaic self-consumption, and renewable electricity procurement. Non-CO₂ controls—covering refrigerants, septic methane, waste and wastewater processes, and fleet combustion—contribute smaller but additive reductions

because they target distinct emission sources. Carbon sinks function as the final balancing mechanism, neutralizing residual emissions after gross reductions have been applied.

Uncertainty in long-term outcomes is primarily associated with future grid emission factors, photovoltaic performance variability, market-based procurement conditions, and the permanence of biological carbon sinks. Nevertheless, under the stated modeling assumptions, both pathways demonstrate technical feasibility for achieving near complete decarbonization within the campus operational boundary by 2040.

3.3. Structural Contribution Analysis of 2040 Reductions

To clarify the relative importance of individual mitigation levers, a structural decomposition of 2040 emission reductions was conducted using Pathway A as the reference configuration. The BAU projection for 2040 (12,026.10 tCO₂e) was compared with the gross and net emissions achieved under the integrated pathway. The analysis indicates that electricity-related measures dominate the reduction profile. Energy-use intensity improvement (S1), photovoltaic self-consumption (S2), and green-power procurement (S3) together account for the majority of gross emission reductions prior to sink application. Among these, renewable electricity procurement provides the largest single reduction in absolute terms, followed by photovoltaic self-consumption and efficiency improvements. This hierarchy reflects the structural composition of campus emissions, where purchased electricity constitutes approximately two-thirds of the baseline footprint. Non-CO₂ mitigation measures—including refrigerant transition (S4), septic methane abatement (S5), fleet electrification and generator reform (S6), and waste/wastewater optimization (S7)—provide smaller but additive reductions. Because these measures target emission sources distinct from electricity use, their effects accumulate without interaction penalties in integrated modeling. Collectively, non-CO₂ controls reduce approximately 8–10% of BAU emissions by 2040. Campus carbon sinks (S8) operate as the balancing mechanism within the integrated framework. At a modeled removal rate of approximately 1800 tCO₂e per year by 2040, sinks offset the residual emissions remaining after gross mitigation, enabling the net-zero outcome in Pathway A. This layered structure—electricity decarbonization first, targeted non-CO₂ reductions second, and removals applied to residual emissions—illustrates a hierarchical mitigation logic that may be applicable to other electricity-dominated institutional systems.

3.4. Sensitivity Analysis

A simplified sensitivity assessment was conducted to evaluate the robustness of 2040 neutrality outcomes under variation in key parameters. Three sources of uncertainty were examined: (i) future grid emission factors, (ii) photovoltaic generation performance, and (iii) permanence of biological carbon sinks.

First, if national grid decarbonization reduces the electricity emission factor by approximately 20% by 2040, BAU emissions would be structurally lower than modeled under the constant-factor assumption. Under such conditions, both integrated pathways would reach neutrality earlier or require reduced green-power procurement volumes. Conversely, if the grid factor declines more slowly than anticipated, electricity-sector mitigation measures become even more critical for meeting neutrality targets.

Second, a $\pm 10\%$ variation in photovoltaic performance would alter 2040 gross emissions by an estimated ± 300 –400 tCO₂e under Pathway B, where reliance on on-site generation is greater. However, such variation would not prevent neutrality under Pathway A due to full coverage of residual grid electricity through certified renewable procurement.

Third, if a more conservative permanence buffer were applied to biological carbon sinks (e.g., 15% rather than 10%), effective credited removals in 2040 would decrease by approximately 200–300 tCO₂e. Under this assumption, Pathway A would remain capable of

achieving neutrality through marginal adjustment of procurement levels, whereas Pathway B would require either additional sink expansion or increased renewable procurement to eliminate the residual.

Overall, the sensitivity analysis indicates that electricity-sector assumptions exert the strongest influence on long-term outcomes. Moderate variation in renewable generation performance or sink permanence does not fundamentally alter the feasibility of achieving near-complete decarbonization within the modeled framework.

4. Discussion

This study demonstrates how institutional carbon neutrality planning can be significantly strengthened through the integration of energy-system modeling and spatial ecosystem carbon accounting. As illustrated in Figure 1, the proposed LEAP–InVEST framework provides a unified analytical structure that links emissions reduction and carbon sequestration within a consistent accounting boundary. Building upon prior research on campus sustainability and decarbonization [21,22], this study moves beyond conventional dual-track approaches by embedding both components within an MRV-aligned framework, thereby improving the transparency and robustness of net-zero assessments.

4.1. Integrated Carbon Accounting and Resolution of Methodological Fragmentation

A central contribution of this study is the resolution of fragmentation between emissions modeling and ecosystem-based carbon accounting. Existing studies often treat these two components separately, resulting in inconsistencies in system boundaries, temporal scales, and accounting logic. While greenhouse gas inventories provide a standardized basis for emissions reporting, they are typically retrospective and do not incorporate dynamic interactions with land-based carbon systems [8]. Similarly, ecosystem carbon assessments using models such as InVEST are frequently presented as static stock estimates rather than temporally evolving flows [14–17].

The integrated framework proposed in this study addresses these limitations by explicitly linking flow-based emissions (LEAP) with stock-based carbon storage (InVEST). Carbon removals are derived from incremental changes in carbon stocks and converted into annualized flows, thereby ensuring compatibility with emissions trajectories. This flow–stock alignment resolves a critical methodological mismatch that has been widely recognized but insufficiently addressed in sustainability research.

Furthermore, the framework enforces boundary consistency by aligning the spatial domain of ecosystem assessment with the organizational boundary of emissions accounting. This prevents the inclusion of external or non-operational carbon sinks that could otherwise lead to inflated neutrality claims. By integrating these elements within a unified accounting structure, the study advances a more rigorous approach to institutional carbon neutrality assessment, consistent with broader calls for improved methodological coherence in climate mitigation research [20].

4.2. Structural Mitigation Pathways and the Role of Hierarchical Decarbonization

The results indicate that electricity consumption is the dominant driver of campus emissions, reinforcing the importance of demand-side and supply-side interventions in achieving deep decarbonization. This finding is consistent with prior studies emphasizing the central role of energy systems in institutional sustainability transitions [20,21]. Within the integrated modeling framework, a clear hierarchical mitigation structure emerges, as conceptualized in Figure 6.

At the first level, demand-side efficiency measures reduce overall energy consumption and limit the scale of required interventions in subsequent stages. At the second

level, supply-side decarbonization—through photovoltaic deployment and green electricity procurement—addresses the carbon intensity of residual energy demand and accounts for the largest share of emissions reduction. At the third level, non-CO₂ mitigation measures, including refrigerant management and methane abatement, provide additional but comparatively smaller contributions due to their limited share in total emissions.

Ecosystem-based carbon sequestration plays a complementary role within this hierarchy. While nature-based solutions are increasingly recognized as important mitigation strategies [11,12], the results of this study confirm that their capacity to offset operational emissions is limited relative to energy-sector interventions. This finding underscores the importance of prioritizing emissions reduction before relying on carbon removals, aligning with established principles of net-zero strategy design [1].

The comparison of alternative pathways further demonstrates that different combinations of efficiency improvements, renewable energy deployment, and carbon removals can achieve similar overall outcomes, albeit with varying levels of reliance on specific mitigation levers. This highlights the flexibility of the framework in supporting scenario-based decision-making under different institutional constraints.

4.3. MRV Alignment, Credibility of Net-Zero Claims, and Framework Transferability

A key implication of this study is the importance of aligning institutional carbon neutrality planning with MRV principles. The proposed framework explicitly separates gross emissions, carbon removals, and net emissions, thereby enabling transparent accounting and reducing the risk of double counting. This separation between gross emissions, removals, and net totals mirrors the accounting logic embedded in established MRV standards such as ISO 27915 and the EU Emissions Trading System, both of which require clear demarcation between captured, transported, and stored carbon across the value chain—a principle equally applicable to institutional-scale carbon neutrality frameworks [31]. This is particularly relevant in the context of increasing scrutiny over carbon neutrality claims, where inconsistencies in accounting practices can undermine credibility. As [19] demonstrate through analysis of carbon market failures in China and elsewhere, even technically sound MRV systems can be compromised by information asymmetry between reporting entities and verifiers, making institutional safeguards and professional accountability as important as methodological rigor in achieving credible net-zero outcomes.

By embedding MRV principles within the analytical structure, the framework provides a robust basis for verifiable net-zero strategies. This aligns with broader efforts to improve the integrity of climate mitigation assessments and supports the development of standardized approaches to institutional carbon accounting [8,22], including ongoing work to design MRV protocols that are both technically rigorous and applicable across different institutional scales and data environments [18].

The conditions under which this framework is most directly transferable to other institutional contexts are worth stating explicitly. The framework is best suited to institutions that: (i) have a defined spatial boundary enabling consistent emissions accounting; (ii) have access to verified GHG inventory data for at least one base year, enabling LEAP calibration; (iii) are located in regions covered by the Sentinel-2 LULC time series, enabling multi-temporal InVEST analysis without proprietary data; and (iv) have managed vegetated land within their boundary that contributes meaningfully to carbon storage. Universities and research campuses in East and Southeast Asia, hospitals with campus-scale facilities, and compact cultural or heritage sites meeting these criteria are natural early adopters. For institutions in data-scarce contexts, the framework remains applicable at a reduced level of precision by substituting IPCC Tier 1 defaults for locally calibrated coefficients and using

publicly available LULC products in place of commissioned surveys—an approach that trades precision for accessibility while maintaining accounting consistency.

Nevertheless, uncertainties remain, particularly with respect to long-term ecosystem dynamics, grid decarbonization trajectories, and the permanence of carbon sinks. Future research may extend this framework by incorporating dynamic emission factors, expanding Scope 3 emissions coverage, and integrating field-based validation of carbon stock estimates. Despite these uncertainties, the results demonstrate that deep decarbonization exceeding 95% relative to BAU is technically feasible within institutional boundaries when emissions reductions and carbon removals are explicitly integrated.

A simplifying assumption adopted throughout this study is that Taiwan's grid electricity emission factor remains constant at 0.495 kgCO₂e/kWh across the 2023–2040 projection period. This choice was made deliberately to isolate the effect of campus-driven mitigation interventions from external grid changes, consistent with standard practice in institutional LEAP modeling and with location-based Scope 2 accounting conventions. In reality, Taiwan's energy transition roadmap targets significant expansion of renewable generation capacity through 2040, which would reduce the grid factor progressively. If the factor declines by 20% to approximately 0.40 kgCO₂e/kWh by 2040—a conservative estimate under current policy trajectories—BAU emissions in 2040 would be approximately 2400 tCO₂e lower than modeled, reducing the absolute mitigation burden on campus-side interventions. Conversely, slower-than-expected grid decarbonization would increase the relative importance of on-campus electricity measures. The sensitivity analysis in Section 3.4 partially captures this range. Future iterations of this framework should incorporate dynamic emission factor trajectories aligned with Taiwan's published renewable energy roadmap.

On the question of model validation, it is important to distinguish between the two model components. For the LEAP emissions component, the base-year calibration against the verified 2023 ISO 14064-1 inventory provides direct empirical grounding. However, validating forward projections requires comparison against future observed emissions, which are not yet available. For the InVEST carbon stock component, the model outputs are inherently bounded by the accuracy of the LULC classification inputs and the representativeness of the carbon pool coefficients applied. Field-based biomass measurements from the NDHU would enable direct validation of carbon stock estimates and identification of any systematic bias introduced by using IPCC Tier 1 defaults rather than locally calibrated values. Contextual plausibility of the model outputs is supported by the consistency of observed carbon stock trends with the documented 2018–2020 cropland-to-forest land-cover transition, and by the alignment of carbon pool coefficients with published field measurements for comparable subtropical forest ecosystems in eastern Taiwan.

5. Conclusions

This study develops and demonstrates an integrated LEAP–InVEST framework for evaluating institutional carbon neutrality pathways by explicitly linking operational emissions modeling with spatial ecosystem carbon accounting. Rather than treating emissions reduction and carbon sequestration as separate analytical domains, the proposed framework reconciles emission flows and carbon stock changes within a unified, MRV-aligned structure. This integration enables consistent estimation of gross emissions, carbon removals, and net emissions, while avoiding double counting and ensuring boundary and temporal alignment.

Applied to the NDHU, the framework provides both methodological and empirical insights. Under a business-as-usual trajectory, emissions are projected to increase modestly to approximately 12,026 tCO₂e by 2040, driven primarily by purchased electricity. Structural decomposition within the framework reveals that electricity-focused

measures—energy-use intensity reduction, photovoltaic self-consumption, and green-power procurement—constitute the dominant mitigation levers. In contrast, non-CO₂ mitigation measures provide complementary but smaller reductions, while ecosystem-based carbon sequestration plays a limited yet critical role in offsetting residual emissions.

The integrated modeling approach further enables systematic comparison of alternative decarbonization pathways. The balanced portfolio pathway achieves full net-zero emissions by 2040 under market-based Scope 2 accounting, with gross emissions reduced to approximately 1703 tCO₂e and fully offset by verified carbon removals of approximately 1800 tCO₂e per year. In contrast, the renewables-leaning pathway achieves approximately 96% reduction relative to BAU, leaving a small residual emissions gap that can be addressed through additional renewable procurement or expanded sink capacity. These results demonstrate that net-zero outcomes are contingent upon the interaction between demand reduction, supply decarbonization, and removal strategies, rather than any single mitigation measure.

Methodologically, the primary contribution of this study lies in establishing a coherent analytical framework that integrates dynamic energy modeling with spatial carbon stock assessment. By converting carbon stock changes into annualized removal flows, the framework resolves the flow–stock inconsistency that has traditionally limited the integration of ecosystem-based mitigation into emissions modeling. Furthermore, the explicit separation of gross emissions, removals, and net emissions provides an MRV-consistent structure that enhances the transparency and credibility of carbon neutrality assessments.

The proposed framework is transferable to other universities and medium-scale institutional systems, particularly those characterized by electricity-dominated emission profiles and managed vegetated landscapes. By embedding emissions reduction and carbon sequestration within a unified analytical structure, the framework enables institutions to move beyond fragmented accounting approaches toward integrated, data-driven net-zero strategies. In doing so, this study contributes to the broader development of robust and verifiable methodologies for institutional carbon neutrality planning.

6. Limitation and Future Research Direction

While the integrated LEAP–InVEST framework demonstrates methodological coherence and analytical transparency, several limitations should be acknowledged to contextualize the findings and guide future research. First, carbon pool coefficients applied in the InVEST model were derived primarily from IPCC Tier 1 default values, supplemented with peer-reviewed literature, due to the absence of site-specific biomass measurements or locally calibrated allometric equations for the dominant vegetation types on the NDHU Shoufeng Campus. Although this approach ensures comparability with international carbon accounting standards, the use of Tier 1 coefficients may underestimate actual carbon stocks in the subtropical humid environment of Hualien County, where site-specific biomass accumulation rates for secondary broadleaf forests can exceed regional default values. Future research should prioritize field-based carbon stock measurements and the development of Tier 2 or Tier 3 coefficients for key campus vegetation types to improve the precision of carbon storage estimates.

Second, the InVEST model treats soil organic carbon changes as immediate outcomes of land-use transitions, without accounting for the time-lag associated with soil carbon stabilization or loss following land-cover change. In reality, soil organic carbon dynamics following cropland-to-forest or built-up transitions may unfold over decades, meaning that the modeled carbon stock changes may not fully reflect actual sequestration rates within the study time-frame (Lal, 2004) [25]. This limitation is particularly relevant for the 2018–2020 period, during which a significant cropland-to-vegetation transition was observed. Third, a temporal mis-

match exists between the InVEST and LEAP model horizons. Empirically grounded carbon stock estimates from InVEST extend only through 2030, while LEAP emissions projections run through 2040. Sink capacity values for 2035 and 2040 in the integrated pathways represent scenario-informed extrapolations bounded by IPCC Tier 1 biomass accumulation rates, and carry greater uncertainty than the near-term empirical estimates. Future iterations should extend the LULC projection and InVEST analysis through 2040 using updated Sentinel-2 imagery, eliminating this gap and enabling direct InVEST-LEAP integration across the full modeling horizon. Fourth, field-based validation of InVEST carbon stock estimates was not conducted in this study due to the absence of campus-level biomass surveys. This represents the highest-priority item for future work and would enable both precision improvement through Tier 2 coefficient development and direct assessment of any systematic bias introduced by the Tier 1 default approach. Fifth, the constant grid emission factor assumption (0.495 kgCO₂e/kWh through 2040) may overstate future Scope 2 emissions if Taiwan's energy transition accelerates. Future work should incorporate dynamic factor projections aligned with Taiwan's renewable energy roadmap. Future research may also expand this framework to incorporate dynamic national grid decarbonization trajectories, broader Scope 3 emission sources, and empirical ground-truth validation of LULC classifications using high-resolution imagery or field surveys.

Author Contributions: Conceptualization, Y.-M.H., S.H.L. and A.K.S.; methodology, A.K.S.; software, A.K.S.; validation, Y.-M.H. and A.K.S.; formal analysis, S.H.L.; investigation, S.H.L.; resources, Y.-M.H.; data curation, Y.-M.H.; writing—original draft preparation, A.K.S.; writing—review and editing, Y.-M.H. and S.H.L.; visualization, Y.-M.H. and S.H.L.; supervision, Y.-M.H. and S.H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Ministry of Education (Taiwan) under the project “Carbon Neutrality—Greenhouse Gas Inventory and Offsetting” (Project No. 114C1101-5.1).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ANN	Artificial Neural Network
BAU	Business-as-Usual
EUI	Energy-Use Intensity
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
ISO	International Organization for Standardization
LEAP	Low Emissions Analysis Platform
LULC	Land Use and Land Cover
MOLUSCE	Modules for Land Use Change Simulation
MRV	Monitoring, Reporting, and Verification
NDHU	National Dong Hwa University
PPA	Power Purchase Agreement
PV	Photovoltaic
REC	Renewable Energy Certificate

Scope 1	Direct emissions from owned/controlled sources
Scope 2	Indirect emissions from purchased electricity
Scope 3	Other indirect upstream/downstream emissions
tC	Metric tons of carbon
tCO ₂ e	Metric tons of CO ₂ equivalent
UTM	Universal Transverse Mercator

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