Design Innovation of Campus Climate-Neutral Energy Systems: From Technology Integration to Economic Optimization

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***Abstract*—As the world accelerates its shift toward carbon neutrality, universities — major energy consumers and influential social leaders — are grappling with unclear strategies for transforming their energy systems in a greener direction. In response, this study introduces an economically driven, multi-period optimization model designed specifically for campus integrated energy systems. Built on a Mixed-Integer Linear Programming (MILP) framework, the model incorporates a range of technologies, including photovoltaic power generation, ground- and air-source heat pumps, electrochemical energy storage, and thermal storage tanks. Using a representative university in China ' s Yangtze River Delta as a case study, the research identifies the most cost-effective combination of technologies and operational strategies to achieve climate neutrality. The findings show that deploying ground source heat pumps to handle base heating demands, alongside large-scale solar photovoltaics and energy storage systems, offers the most economically practical solution. Compared with traditional energy setups, the optimized system can cut Scope 1 and Scope 2 carbon emissions by more than 85%. Under projected grid decarbonization trends and tiered carbon pricing policies, the campus could realistically reach carbon neutrality by around 2045. Overall, this study delivers a practical decision-making framework that balances technical feasibility with economic efficiency, offering valuable guidance for university energy planning in China and other regions with similar climate conditions.**

Keywords—Climate Neutrality; Campus Energy System; Technology Integration; Economic Optimization; Mixed-Integer Linear Programming

I. INTRODUCTION

In response to the escalating threat of global climate change, the Paris Agreement set a clear target: keep the rise in global average temperature well below 2 ° C above pre-industrial levels and strive to limit it to 1.5 ° C. This commitment has accelerated the global shift toward renewable energy and intensified efforts to reduce greenhouse gas emissions [1]. As the world ' s largest carbon emitter, China has pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Meeting these goals will require deep, system-wide transformations across every sector of its economy and society [2].

Universities, often described as "micro-societies" that combine education, research, and daily living, are characterized by dense populations and high energy demand. Their per capita energy use and carbon emissions typically exceed the broader social average, positioning them as both key contributors to urban emissions and ideal demonstration sites for carbon neutrality initiatives [3].

At present, however, many Chinese university campuses still rely heavily on fossil fuels. Their energy systems tend to operate with relatively low efficiency and are often managed in a fragmented or extensive manner. Electricity and natural gas dominate campus energy consumption, with electricity accounting for as much as 77% of total usage [4]. This structure leads not only to high operating costs but also to significant carbon emissions, creating tension with China ' s " dual carbon " goals and the broader vision of green campus development. As a result, redesigning and optimizing campus energy systems to create clean, low-carbon, secure, and efficient integrated systems has emerged as an urgent scientific and practical challenge.

Researchers around the world have explored various pathways for low-carbon campus transitions. Some studies emphasize individual technologies, such as expanding photovoltaic (PV) installations [5], deploying ground source heat pumps (GSHPs) [6], or utilizing biomass energy [7]. Others adopt holistic approaches, using tools like Life Cycle Assessment (LCA) to quantify overall campus carbon footprints and propose broad emission-reduction strategies [8]. For example, Cornell University developed a roadmap to achieve carbon neutrality by 2035 by designing an integrated system that combines geothermal heating, lake source cooling, and multiple renewable energy technologies, optimized through Mixed-Integer Non-Linear Programming (MINLP) [9]. Research focused on Chinese campuses similarly suggests that large-scale renewable deployment and systematic optimization are essential to achieving carbon neutrality [10].

Despite these advances, several limitations remain. Many studies concentrate either on specific technologies or high-level strategies, without offering comprehensive system designs that integrate both technical feasibility and economic performance. In addition, some optimization models are simplified or nonlinear, making it difficult to ensure global optimality and to fully incorporate China ' s unique grid structure, energy pricing mechanisms, and policy instruments such as tiered carbon pricing. Furthermore, most detailed case studies originate from Europe and North America, leaving a relative gap in systematic optimization research tailored to Chinese universities — particularly those in the

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distinct climatic and energy context of the Yangtze River Delta region.

To address these gaps, this study proposes an innovative design framework for a climate-neutral campus energy system, using a comprehensive university in the Yangtze River Delta as a case study. The research develops a Mixed-Integer Linear Programming (MILP) model aimed at minimizing total life-cycle costs while jointly optimizing both capacity planning and operational strategies for an integrated system that includes PV generation, energy storage, heat pumps, and thermal storage.

The central question guiding this work is: What combination of technologies and operational strategies can most economically and effectively move a university campus toward carbon neutrality while reliably meeting diverse energy demands? To answer this, the study clearly defines system boundaries, focusing on reducing Scope 1 emissions (direct emissions) and Scope 2 emissions (indirect emissions from purchased electricity). It evaluates the emission-reduction potential and economic implications of different technical pathways, ultimately proposing a replicable and scalable decision-support framework for sustainable energy transformation at universities in China and other regions with similar conditions.

The remainder of this paper is structured as follows. Section 2 reviews related research on campus integrated energy system optimization and carbon neutrality pathways. Section 3 introduces the MILP model, including its objective function, decision variables, and key constraints. Section 4 presents the energy demand characteristics, technical parameters, and cost data of the case study university. Section 5 reports and analyzes the optimization results from technical, economic, and carbon-reduction perspectives. Finally, Section 6 concludes the study and outlines directions for future research.

II. Literature Review

In recent years, as global concern over climate change has intensified, reducing carbon emissions and transforming energy systems on university campuses have become prominent research themes. Existing studies in this field generally fall into three main categories: campus carbon footprint accounting and mitigation pathway analysis, application of key technologies in integrated energy systems, and energy system integration with optimization modeling.

In terms of carbon footprint accounting, researchers commonly apply Life Cycle Assessment (LCA) methods and the IPCC emissions inventory framework to quantify greenhouse gas emissions associated with university operations. Findings consistently show that purchased electricity (Scope 2 emissions) represents the dominant source of campus carbon emissions, often accounting for more than 70% of the total [11][12]. For instance, research on a medium-sized university in eastern China revealed that electricity consumption alone contributed 77% of total campus emissions [4]. Based on such assessments, scholars have proposed a range of emission reduction strategies, including improving building energy efficiency, expanding renewable energy adoption, optimizing waste management, and promoting green transportation. However, many of these studies remain at the level of qualitative strategic analysis or evaluate single mitigation measures in isolation. Comprehensive cost – benefit assessments that capture the synergistic effects of multiple technologies are still limited.

At the technological level, photovoltaic (PV) systems, ground and air source heat pumps (GSHP/ASHP), and energy storage technologies have attracted significant attention due to their technical maturity and strong decarbonization potential. PV systems are widely regarded as a cornerstone for enhancing campus energy self-sufficiency and decarbonizing electricity supply [5][10]. Heat pumps, with coefficients of performance (COP) often exceeding 3.0, are viewed as an effective alternative to traditional gas boilers and a key enabler of heating electrification [13]. Meanwhile, both electrochemical and thermal energy storage systems play a vital role in mitigating renewable energy intermittency, enabling peak – valley electricity price arbitrage, and improving overall system flexibility [14]. Although research on these individual technologies is well developed, effectively integrating them into a unified energy system and achieving coordinated optimization across multiple energy carriers—electricity, heating, and cooling—remains a complex challenge.

To tackle this issue, mathematical optimization methods have increasingly been applied to campus energy system design. Early studies primarily relied on Linear Programming (LP) to address dispatch problems in single-energy systems. As system configurations became more complex, Mixed-Integer Linear Programming (MILP) emerged as the dominant approach in Integrated Energy System (IES) planning and design, since it can simultaneously handle continuous variables (such as equipment capacity and output) and discrete decisions (such as equipment installation or operational status) [15][16]. Several studies have employed MILP for campus energy system optimization. For example, reference [9] developed a Mixed-Integer Non-Linear Programming (MINLP) model to explore Cornell University's pathway to 100% renewable energy. However, the non-convex structure of the MINLP model made it challenging to guarantee a global optimal solution. Other research has applied MILP to optimize campus microgrid operations or determine optimal PV and energy storage configurations, including energy exchanges between campuses and nearby residential areas [17].

Despite their methodological strengths, these studies often exhibit several limitations. First, many models use relatively low temporal resolution (e.g., seasonal or monthly averages), which restricts their ability to capture hourly operational dynamics and renewable energy variability. Second, techno-economic parameters are frequently simplified, limiting accurate representation of full life-cycle costs. Third, external policy factors — such as time-of-use electricity pricing, carbon trading schemes, and stepped carbon pricing mechanisms—are rarely incorporated in detail, even though they can significantly influence optimal system design and operational strategies.

Overall, while substantial progress has been made in campus carbon accounting, technology assessment, and optimization modeling, there remains a clear need for a comprehensive framework that integrates detailed technological options, long-term investment planning, short-term operational optimization, and complex economic and policy conditions. This gap is particularly evident in empirical research focused on Chinese universities. Against this backdrop, the present study develops a high-resolution MILP model that systematically integrates multiple low-carbon energy technologies and optimizes them from an economic perspective. The goal is to provide a more rigorous, practical, and policy-relevant decision-making foundation for advancing carbon-neutral energy transitions at universities in China and other regions facing similar challenges.

III. Methodology

To guide the campus energy system toward climate neutrality in a cost-effective way, this study develops a multi-period Mixed-Integer Linear Programming (MILP) model. Within a unified analytical framework, the model simultaneously optimizes long-term investment decisions—such as equipment capacity planning — and short-term operational decisions, including hourly dispatch strategies. By coordinating these two dimensions, it identifies the least-cost pathway that satisfies energy demand requirements while adhering to carbon emission constraints.

A. System Framework

The Integrated Energy System (IES) framework designed for the campus in this study is illustrated in Figure 1. The system links three major energy streams—electricity, heating, and cooling — into a coordinated structure that combines energy supply, conversion, and storage technologies within a single platform. The main components are outlined below.

1) Energy Supply Module

This module covers electricity purchased from the external grid as well as on-site distributed photovoltaic (PV) generation. Grid electricity procurement follows a time-of-use (TOU) pricing structure, which differentiates tariffs into peak, flat, and valley periods. This pricing mechanism directly influences operational scheduling and cost optimization.

2) Energy Conversion Module

The conversion module enables multi-energy coordination and enhances overall system efficiency. Its primary technologies include:

- Ground Source Heat Pump (GSHP) / Air Source Heat Pump (ASHP): These high-efficiency, electricity-driven systems provide both heating and cooling services, replacing conventional gas-fired boilers and standalone chillers.
- Electric Chiller (EC): This unit functions as a conventional cooling source, primarily meeting peak cooling loads or supplementing the output of heat pumps when necessary.

3) Energy Storage Module

The storage module improves system flexibility by mitigating renewable energy intermittency and leveraging peak – valley electricity price differences. It includes:

- Battery Energy Storage System (BESS): Facilitates electricity time-shifting, storing power during low-price periods or surplus PV generation and discharging during peak demand.
- Hot Water Storage Tank (HWST): Stores surplus thermal energy produced by heat pumps for later release during periods of high heating demand.
- Chilled Water Storage Tank (CWST): Accumulates cooling energy during off-peak electricity periods and discharges it during peak cooling hours.

4) Energy Demand Module

This module represents the campus' s hourly electricity, heating, and cooling load profiles, reflecting the dynamic energy requirements of campus buildings.

Together, these interconnected modules form a comprehensive campus IES capable of coordinating multiple energy flows to support low-carbon, cost-effective operation.

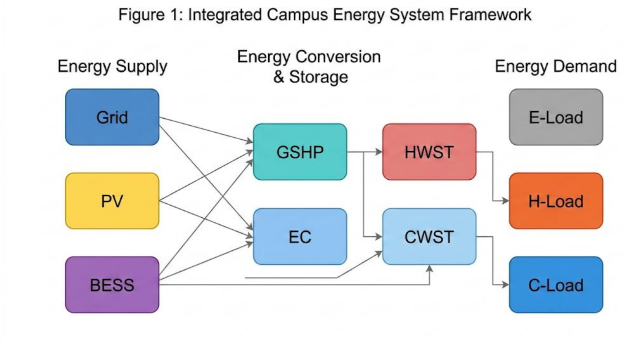

Fig. 1. Campus Integrated Energy System Framework

B. Mathematical Model

The model is formulated on an annual basis with an hourly resolution (t = 1, 2, ⋯, 8760). Its objective is to minimize the system' s Total Annualized Cost (TAC) while satisfying energy demand and carbon emission constraints.

1) Objective Function

The objective function includes three components: Annualized Investment Cost (AIC), Annual Operation and Maintenance Cost (AOC), and Annual Energy Consumption Cost (AEC), as expressed in Equation (1):

$$\min TAC = AIC + AOC + AEC \tag{1}$$

a) Annualized Investment Cost (AIC)

AIC represents the annualized value of the initial capital investment (CAPEX) for all newly installed technologies. The capital cost is converted into an equivalent annual cost using the Capital Recovery Factor (CRF):

$$AIC = \sum_{tech} (CAPEX_{tech} \times CRF_{tech}) \tag{2}$$

$$CRF = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{3}$$

where:

- i is the discount rate,
- n is the equipment lifetime

b) Annual Operation and Maintenance Cost (AOC)

AOC is typically estimated as a fixed percentage of the initial investment cost, reflecting routine operation and maintenance expenses.

c) Annual Energy Consumption Cost (AEC)

AEC mainly refers to the total annual cost of electricity purchased from the external grid, taking time-of-use (TOU) pricing into account:

$$AEC = \sum_{t=1}^{8760} (P_{grid}(t) \times Price_{grid}(t)) \quad (4)$$

2) *Main Constraints*

To ensure physical feasibility and safe operation, the model incorporates several categories of constraints.

a) Energy Balance Constraints

For each hour ttt, supply must equal demand for electricity, heating, and cooling.

Electricity balance:

$$P_{grid}(t) + P_{pv}(t) + P_{bess,dis}(t) = P_{load}(t) + P_{bess,ch}(t) + P_{hp,elec}(t) + P_{ec,elec}(t) \quad (5)$$

(Grid purchase + PV generation + BESS discharge = Electricity load + BESS charge + Heat pump consumption + Electric chiller consumption)

Heating balance:

$$Q_{hp,heat}(t) + Q_{hws,t,dis}(t) = Q_{load,heat}(t) + Q_{hws,t,ch}(t) \quad (6)$$

(Heat pump generation + HWST discharge = Heating load + HWST charge)

Cooling balance:

$$Q_{hp,cool}(t) + Q_{ec,cool}(t) + Q_{cwst,dis}(t) = Q_{load,cool}(t) + Q_{cwst,ch}(t) \quad (7)$$

b) Equipment Operational Constraints

PV generation:

PV output depends on installed capacity and solar irradiance:

$$P_{pv}(t) = Cap_{pv} \times Ir(t) \times \eta_{pv} \quad (8)$$

Heat pump performance:

Heating and cooling output are linked to electricity input through the Coefficient of Performance (COP):

$$Q_{hp,heat}(t) = P_{hp,elec}(t) \times COP_{hp,heat} \quad (9)$$

$$Q_{hp,cool}(t) = P_{hp,elec}(t) \times COP_{hp,cool} \quad (10)$$

Energy storage systems:

Battery and thermal storage operation must satisfy state-of-charge (SOC) transition equations and charging/discharging limits:

$$SOC(t) = SOC(t-1) \times (1-\delta) + (P_{ch}(t) \times \eta_{ch} - P_{dis}(t)/\eta_{dis}) \times \Delta t \quad (11)$$

(Current SOC = Previous SOC × (1 − self-discharge rate) + net charged energy)

c) Capacity Constraints

For all technologies, operational output cannot exceed installed capacity:

$$0 \le P_{tech}(t) \le Cap_{tech} \quad (12)$$

d) Carbon Emission Constraint

Total annual carbon emissions—primarily from grid electricity purchases—must remain within a predefined emission cap:

$$\sum_{t=1}^{8760} (P_{grid}(t) \times EF_{grid}) \le Emission_{Cap} \quad (13)$$

where EF_{grid} represents the carbon emission factor of the power grid.

C. *Data Sources and Processing*

The data used in this study can be grouped into three main categories:

1) *Load Data:*

Hourly electricity, heating, and cooling demand data for the entire year of 2023 were obtained from publicly accessible or shareable datasets. These data were processed to construct a representative campus load profile (see Appendix for details on the data structure and preprocessing steps), ensuring that the model inputs can be readily replicated.

2) *Meteorological Data:*

Hourly solar irradiance, ambient temperature, and other relevant meteorological variables were sourced from publicly available weather databases. The meteorological data were synchronized with the load timeline to calculate photovoltaic (PV) generation output and the heat pump Coefficient of Performance (COP), allowing all weather-dependent inputs to be reproduced.

3) *Techno-economic Parameters:*

Key parameters — including capital investment costs, operation and maintenance (O&M) costs, equipment lifetimes, and efficiency/performance indicators for PV systems, energy storage, and heat pumps — were compiled from peer-reviewed studies and publicly verifiable cost benchmarks. These values were cross-checked for consistency using references [16] and [17], enabling independent verification of major assumptions.

All datasets underwent preprocessing procedures, such as outlier detection and removal, as well as missing value imputation, to ensure the robustness and reliability of the model inputs. The MILP model was developed using an open and reproducible modeling workflow (e.g., open-source algebraic modeling languages) and can be solved with widely available MILP solvers. This ensures that the entire computational process can be replicated without dependence on proprietary software licenses.

IV. Case Study and Data

A. *Overview of the Case Study University*

This research focuses on an anonymized yet representative comprehensive university campus located in the Yangtze River Delta region of China. The assumed campus scale — such as land area and population size — is used solely to define a typical energy demand scenario and can be flexibly adjusted by readers to reflect local conditions.

The campus includes a diverse mix of building types, such as teaching facilities, research laboratories, libraries, student dormitories, dining halls, and administrative offices. This functional diversity makes it a representative case for analyzing complex and varied energy use patterns.

Climatically, the Yangtze River Delta falls within the “ hot summer and cold winter ” zone. As a result, the campus experiences substantial cooling demand during summer and significant heating demand during winter. These pronounced seasonal variations provide a suitable context for examining the seasonal optimization and coordinated operation of integrated energy systems.

B. *Energy Load Characteristics*

Hourly electricity, heating, and cooling load profiles for the full year of 2023 were developed using publicly accessible or shareable datasets, following a transparent preprocessing methodology. The resulting representative load curves (see Figure 2) show clear seasonal and daily fluctuations in campus energy demand.

1) *Electricity Load:*

Electricity is required year-round. Demand peaks during the summer months due to intensive air-conditioning use and shows a secondary peak in winter. On a daily scale, electricity consumption is highest during daytime hours (approximately 8:00 – 20:00) and declines significantly at night.

2) *Heating Load:*

Heating demand is concentrated in the winter season, typically from November to March. Compared with electricity and cooling loads, the daily variation in heating demand is relatively moderate, with less pronounced peak – valley differences.

3) *Cooling Load:*

Cooling demand is concentrated in the summer months (June to September) and is strongly correlated with ambient temperature. It typically reaches its daily maximum in the early afternoon, around 14:00, when outdoor temperatures are highest.

These load characteristics highlight the importance of coordinated multi-energy management and seasonal optimization in designing a cost-effective and low-carbon campus energy system.

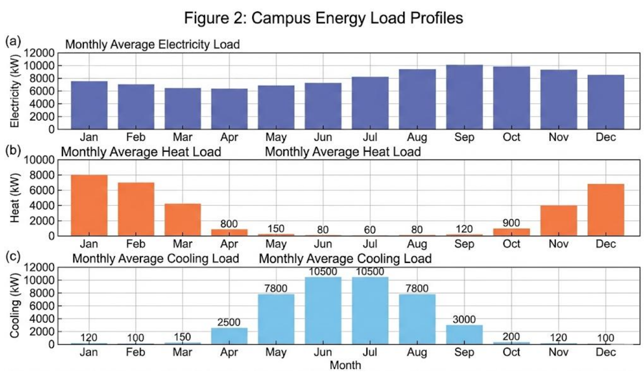

Fig. 2. Monthly Average Energy Load Profiles of the Case Study Campus (representative load profiles derived from reproducible input dataset)

C. *Techno-economic Parameters*

The main technologies included in the model—along with their corresponding economic and performance parameters—are summarized in Table I. All cost figures were collected from publicly verifiable price benchmarks and recent academic literature published in 2024 [16][17][18]. For consistency, all monetary values have been converted into Chinese Yuan (CNY).

TABLE I. KEY TECHNO-ECONOMIC PARAMETERS

Technology	Unit Investment Cost	O&M Cost (% of CAPEX)	Lifetime (years)	Efficiency/Performance Parameter
Photovoltaic (PV)	3.5 CNY/Wp	1.5%	25	Conversion Efficiency: 18%
Li-ion BESS	1.5 CNY/Wh	2.0%	15	Round-trip Efficiency: 95%
Ground Source HP (GSHP)	2000 CNY/kW	2.0%	20	COP (Heating): 4.0, COP (Cooling): 5.0
Air Source HP (ASHP)	1200 CNY/kW	2.5%	15	COP (Heating): 3.0, COP (Cooling): 3.5
Hot Water Storage (HWST)	400 CNY/kWh	1.0%	20	Storage/Release Efficiency: 98%
Chilled Water Storage (CWST)	350 CNY/kWh	1.0%	20	Storage/Release Efficiency: 98%

D. *Economic and Environmental Parameters*

1) *Electricity Price:*

The model adopts a representative time-of-use (TOU) tariff applicable to large industrial consumers in the Yangtze River Delta region. The peak price (8:00 – 12:00 and 17:00 – 21:00) is 1.2 CNY/kWh, the flat price (12:00 – 17:00 and 21:00 – 24:00) is 0.8 CNY/kWh, and the valley price (0:00 – 8:00) is 0.4 CNY/kWh.

2) *Discount Rate:*

A discount rate of 6% is applied to calculate the annualized investment cost of capital-intensive equipment.

3) *Grid Emission Factor:*

The carbon emission factor of grid electricity is set at 0.58 tCO_2 /MWh, reflecting the average level of the East China Power Grid.

4) *Carbon Price:*

To assess the potential impact of a future carbon trading market, the model incorporates a tiered carbon pricing mechanism. Emissions exceeding a predefined baseline are subject to a carbon cost, simulating the economic pressure imposed by carbon regulation policies.

V. RESULTS AND DISCUSSION

This section presents and interprets the optimization results obtained from the MILP model, covering the optimal system configuration, annual energy flows, economic performance, and carbon emission reductions. Key findings are then discussed in depth.

A. *Optimal System Configuration and Economic Analysis*

To minimize the Total Annualized Cost (TAC), the model identifies the optimal configuration of the campus energy system, as summarized in Table II. The results indicate a clear preference for substantial investment in renewable energy generation and high-efficiency energy conversion technologies.

The Ground Source Heat Pump (GSHP) emerges as the primary heating and cooling technology, with installed capacity sufficient to meet the majority of the campus ' s base thermal load. This reflects its high efficiency and strong economic performance under the assumed electricity pricing and carbon constraints.

The Photovoltaic (PV) system is expanded to the maximum capacity permitted by available rooftop and parking-lot space, highlighting the economic and environmental value of on-site renewable electricity generation. Maximizing PV deployment significantly reduces grid electricity purchases and associated carbon emissions.

To manage the variability of PV output and capitalize on time-of-use (TOU) electricity price differences, the model also recommends considerable investment in Battery Energy Storage Systems (BESS), along with hot water and chilled water storage tanks. These storage technologies enhance system flexibility, enable electricity price arbitrage, and support load shifting between peak and valley periods.

Overall, the optimal configuration demonstrates a coordinated strategy that combines large-scale renewable deployment, electrified heating and cooling, and multi-form energy storage to achieve both economic efficiency and deep carbon reduction.

From an economic standpoint, the optimized system achieves a Total Annualized Cost (TAC) of approximately 65 million CNY. The breakdown of this cost structure is illustrated in Figure 3.

The Annualized Investment Cost (AIC) represents the largest proportion—about 60% of the total—primarily driven by the significant upfront capital required for photovoltaic (PV) systems, battery energy storage systems (BESS), and ground source heat pumps (GSHP). The Annual Operation and Maintenance Cost (AOC) accounts for roughly 15%, while the Annual Energy Consumption Cost (AEC) makes up the remaining 25%.

Although the system entails considerable initial investment, the results show that it can reduce total life-cycle costs by approximately 15 – 20% compared to a conventional energy supply model that depends entirely on grid electricity and natural gas. These savings stem largely from reduced reliance on externally purchased energy.

Overall, the findings suggest that while the transition to a low-carbon campus energy system requires substantial upfront capital, the long-term operational savings and improved energy efficiency make the transformation economically viable.

TABLE II. OPTIMAL ENERGY SYSTEM CONFIGURATION

Technology	***Optimized Capacity***	***Unit***
Photovoltaic (PV)	25	MWp
Battery Energy Storage (BESS)	50	MWh
Ground Source Heat Pump (GSHP)	30	MW
Hot Water Storage Tank (HWST)	200	MWh
Chilled Water Storage Tank (CWST)	300	MWh

Figure 3: Economic Analysis of Optimized Energy System

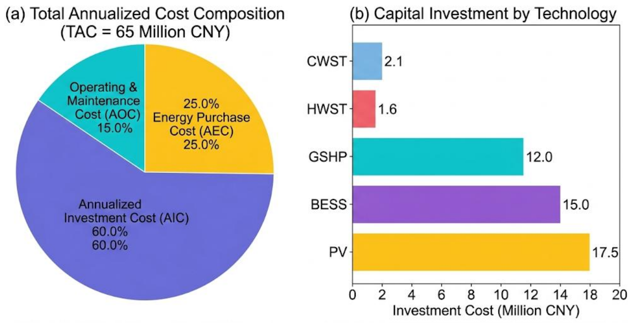

Fig. 3. Total Annualized Cost (TAC) Analysis (representative dataset)

B. *Annual Energy Flow Analysis*

Figure 4 presents the annual energy flow of the optimized system using a Sankey diagram, offering an intuitive view of how electricity, heating, and cooling are supplied and utilized.

The results show that approximately 40% of the campus' s total electricity demand is met by on-site photovoltaic (PV) generation, while the remaining portion is supplied by the external grid. During peak daylight hours, PV generation not only satisfies real-time electricity loads but also produces surplus power, which is stored in the Battery Energy Storage System (BESS). At night or during periods of low solar irradiance, the BESS discharges to support campus demand, effectively smoothing fluctuations in renewable generation.

Notably, a large share of the electricity consumed by the heat pump system is sourced from PV and BESS, demonstrating strong coupling between renewable electricity and electrified heating and cooling. This coordinated operation enhances overall system efficiency and reduces dependence on grid electricity.

In addition, the thermal storage tanks play a strategic role in cost optimization. They store thermal energy during nighttime valley-price periods and release it during daytime peak-price hours. This load-shifting strategy lowers grid purchases during high-tariff periods and reduces overall operational costs.

Together, these energy flow patterns highlight the integrated and flexible nature of the optimized system, where renewable generation, storage, and high-efficiency conversion technologies work in synergy to improve both economic and environmental performance.

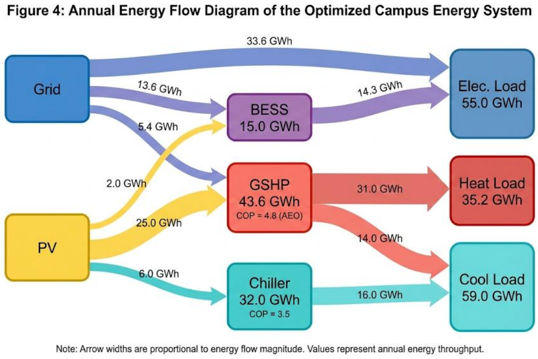

Fig. 4. Annual Energy Flow Diagram of the Optimized Campus Energy System (representative dataset)

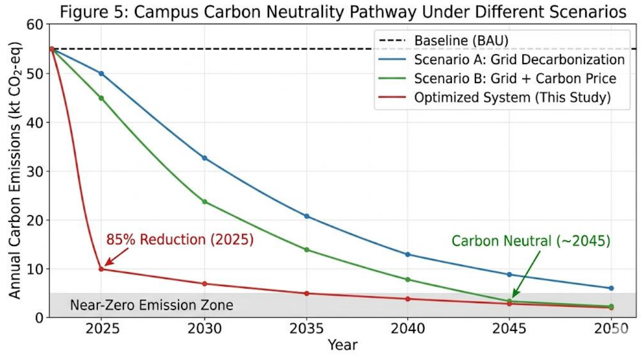

Fig. 5. Campus Carbon Neutrality Pathway Under Different Scenarios (representative dataset)

C. Carbon Reduction Benefits and Pathway Analysis

The optimized energy system delivers substantial carbon reduction benefits. Compared with the baseline scenario (a representative 2023 reference case constructed from the reproducible input dataset), total annual Scope 1 and Scope 2 emissions decrease from approximately 55,000 tons to about 8,000 tons—an overall reduction of 85.5%.

This dramatic decline is driven by two primary factors. First, large-scale photovoltaic (PV) deployment significantly reduces reliance on grid electricity, which carries a relatively high carbon emission factor. Second, the electrification of heating through ground source heat pump technology fully replaces conventional natural gas boilers, thereby eliminating nearly all Scope 1 direct emissions associated with on-site fuel combustion.

To further assess the pathway toward full carbon neutrality, two forward-looking scenarios were developed:

- Scenario A (Grid Decarbonization): Assumes that by 2040, the carbon emission factor of the East China Grid decreases by 50%, reflecting a substantially higher share of renewable energy in the regional power mix.
- Scenario B (Carbon Pricing Mechanism): Building upon Scenario A, a tiered carbon pricing scheme is introduced, applying a carbon cost of 100–300 CNY per ton to emissions exceeding an allocated allowance.

The simulation results (Figure 5) indicate that under Scenario A, campus emissions decline further to approximately 4,000 tons per year, driven solely by upstream grid decarbonization. Under Scenario B, the additional economic pressure from carbon pricing encourages further system optimization—such as expanded storage capacity to absorb more PV generation—ultimately reducing annual emissions to below 1,000 tons.

The small remaining emissions could be offset through mechanisms such as purchasing Green Power Certificates (GPCs) or investing in certified carbon sinks. Under these combined measures, the campus could realistically achieve full carbon neutrality by around 2045.

D. Sensitivity Analysis

To evaluate the robustness of the optimization outcomes, a sensitivity analysis was performed on several key parameters. The results are summarized in Figure 6.

Panel (a) presents a tornado diagram showing how the Total Annualized Cost (TAC) responds to ±20% variations in major input parameters. The analysis reveals that TAC is most sensitive to changes in electricity prices, followed by photovoltaic (PV) investment costs and the discount rate. This indicates that future fluctuations in electricity tariffs and continued declines in PV costs will play a decisive role in shaping the system's overall economic performance. In contrast, variations in other parameters have comparatively smaller impacts on total cost.

Panel (b) illustrates how carbon pricing influences the optimal system configuration. As the carbon price rises from 0 to 300 CNY/tCO_2 , the model responds by increasing installed PV capacity from 25 MWp to 35 MWp and expanding battery energy storage system (BESS) capacity from 50 MWh to 75 MWh. At the same time, annual CO_2 emissions decline from 8.0 kt to 4.0 kt.

These results demonstrate that carbon pricing effectively strengthens the economic incentive to invest in additional renewable generation and storage capacity. In other words, well-designed carbon policies can significantly accelerate the transition toward deeper decarbonization while reshaping optimal infrastructure investment decisions.

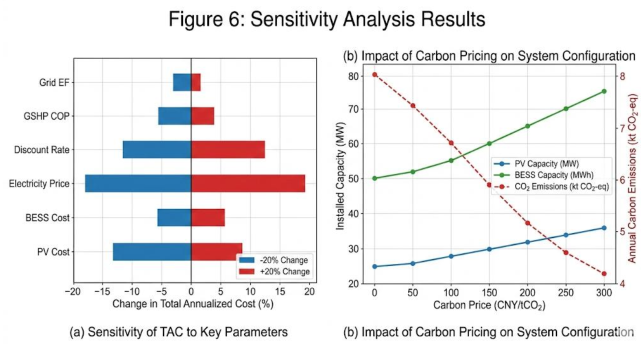

Fig. 6. Sensitivity Analysis Results (representative dataset)

VI. Discussion

The findings of this study share both common ground and clear distinctions when compared with the Cornell University case [8]. In both cases, ground source heat pumps (GSHPs) play a central role in meeting base thermal loads, and both approaches emphasize the coordinated integration of multiple low-carbon technologies. However, the two cases differ in their core system configurations. Owing to differences in climate conditions and electricity pricing structures, photovoltaic (PV) systems and battery energy storage systems (BESS) exhibit stronger economic competitiveness in the Yangtze River Delta context, becoming the backbone of the optimized configuration. In contrast, the Cornell case placed greater emphasis on geothermal heating and biomass energy. This comparison highlights that there is no universal pathway to campus carbon neutrality; instead, solutions must be tailored to local resource availability, climatic conditions, and economic and policy environments.

Relative to existing domestic research, this study contributes a more detailed and integrated optimization framework. By employing an hourly time resolution, the model captures renewable energy variability and storage charge–discharge dynamics with greater precision, leading to more realistic capacity planning outcomes. Moreover, by jointly optimizing long-term investment decisions and short-term operational strategies within a unified framework, the model avoids the common planning limitation of "prioritizing construction over operation." This integrated approach ensures life-cycle economic optimality rather than focusing solely on upfront infrastructure deployment.

Nevertheless, several limitations remain. First, the model relies on deterministic technical and economic parameters, without explicitly accounting for uncertainties such as future cost reductions or performance improvements in emerging technologies. Second, flexibility resources such as demand-side response and vehicle-to-grid (V2G) charging and discharging are not included, although they may offer additional potential for cost savings and emission reductions. Finally, non-technical measures—such as behavioral energy conservation and institutional management improvements—also influence real-world energy performance but are difficult to quantify within the current modeling framework.

VII. Conclusion

This study tackles the intricate challenge of guiding Chinese universities toward climate neutrality by introducing a comprehensive method for designing and optimizing campus energy systems using Mixed-Integer Linear Programming (MILP). Focusing on a case study of a representative university in the Yangtze River Delta, the research assesses both the economic feasibility and carbon reduction potential of various low-carbon technologies, offering a realistic roadmap to achieving carbon neutrality on campus.

Key findings of the study include:

- Technical Pathway: Under current technological and financial conditions, the most cost-effective solution for transitioning a university energy system to low carbon involves leveraging ground source heat pumps for baseline heating and cooling, expanding the use of distributed photovoltaics, and installing large-scale battery and thermal energy storage to boost system flexibility.
- Economic Viability: While the initial investment for a low-carbon transition is considerable, strategic system configuration and operational optimization lead to a total life-cycle cost that is actually lower than that of conventional energy systems. This validates the long-term economic advantage of pursuing carbon neutrality.
- Emission Reduction Impact: The proposed integrated energy system can cut the campus's Scope 1 and Scope 2 emissions by more than 85%. With continued grid decarbonization and supportive policies like carbon pricing, full campus carbon neutrality could be achieved around 2045 by combining technology-driven reductions with limited carbon offsetting.

The study's core contribution lies in delivering a refined, practical decision-making tool for planning campus energy systems. The model not only identifies the best mix of technologies and their capacities but also provides detailed, hourly operational strategies, equipping energy managers with actionable guidance. Findings highlight the importance of adapting solutions to local contexts and demonstrate that economic and environmental benefits can go hand in hand through smart system integration.

Looking ahead, future research could incorporate uncertainty analysis to account for evolving energy prices, technology costs, and policies. It could also explore more flexible resources like demand-side response and coordinated EV charging/discharging, as well as multi-stakeholder energy trading models, to further enhance the value of campus energy networks.

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AUTHOR CONTRIBUTIONS

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COMPETING INTERESTS

The authors declare no competing interests.