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Planning High-PV Penetration Park: Enhancing Local PV Utilization and Economic Efficiency through Multi-Energy Storage

Junlang Zhu,[1] Libin Han,[2] Juan Yu,[1] Xiangzhe Xi,[3] Yang Zhao,[1] and Borong Lin[1,*]

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GRAPHICAL ABSTRACT

PUBLIC SUMMARY

- Introduced a bi-level optimization framework for energy planning in high-PV-penetration parks.
- Demonstrated that optimized configurations can increase local PV utilization from 33.6% to 73.0%, reducing annualized costs by 30.2%.
- Showed that battery storage becomes crucial under high PV penetration, while thermal storage plays a supplementary role, with charging and discharging patterns aligned to daytime and nighttime/off-peak hours.
- Explored external resource integration, boosting PV utilization to 81.6% and reducing the levelized cost of consumed electricity (LCOCE) by 6.5%.
- Highlighted the need for internal multi-energy flexibility and external resource integration to optimize PV absorption, cost-effectiveness, and carbon reduction in net-zero parks.

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Large airports have substantial energy consumption demands while possessing significant spatial resources for photovoltaic (PV) development. However, addressing the mismatch between PV generation and airport electricity demand to achieve efficient local consumption and optimal energy utilization remains a critical research challenge. This study investigates energy planning strategies for high-PV-penetration parks under net-zero development, using a major Chinese airport terminal expansion as a case study. The proposed bi-level optimization framework jointly determines installed capacities and annual hourly operation of multi-energy systems, integrating cooling, heating, and electricity with flexible resources including battery storage, chilled/hot water storage, and uni/bi-directional EV charging. A net-zero carbon constraint through carbon trading ensures environmental alignment while minimizing annualized costs. Results demonstrate local PV utilization improves from 33.6% without flexible storage to 73.0% with optimized configuration, accompanied by 30.2% cost reduction. Battery storage gains greater importance under high PV penetration due to unconstrained flexibility, while thermal storage serves supplementary roles. The system follows daytime charging and nighttime or off-peak discharging patterns. Beyond internal optimization, the study explores strategies for incorporating external resources such as adjacent buildings and surrounding EV fleets. Results show that these measures further raise PV utilization to 81.6% and reduce the levelized cost of consumed electricity (LCOCE) by 6.5%. Integrating surrounding buildings enhances source-load matching and reduces storage demand, while staff vehicles and external vehicle fleets substitute partial battery capacity. The findings highlight that high-PV parks require both internal multi-energy flexibility and external resource integration for efficient PV absorption, cost-effectiveness, and carbon reduction. This research establishes a paradigm for zero-carbon park planning under policy constraints, offering transferable insights for transport hubs and urban districts maximizing local PV consumption while improving economic performance.

INTRODUCTION

Large transport hubs such as airports are among the most energy-intensive building clusters in modern cities, characterized by continuous operation, complex functional zones, and high electricity demand for lighting, HVAC systems, and transport services.[1] At the same time, airports possess extensive rooftop and open-space resources that are well suited for large-scale photovoltaic (PV) deployment. Thus, airports are increasingly recognized as complex energy hubs rather than simple transport infrastructures. With the rapid decline in PV costs and the global push toward carbon neutrality, airports are increasingly regarded as promising candidates for high-PV-penetration and net-zero energy development.

However, the energy profile of airports poses a fundamental challenge for PV utilization. Unlike typical commercial buildings with daytime peak loads, airport electricity demand often remains high during nighttime due to lighting, security, and flight operations. This temporal mismatch between PV generation and load demand leads to low local consumption rates when PV capacity is scaled up. Without adequate flexibility mechanisms, large amounts of midday PV generation may be curtailed or exported to external grids, reducing both economic and environmental benefits of renewable deployment. Recent policy shifts in China and other regions further restrict surplus PV export for large industrial and commercial consumers, making traditional "generate-and-export" strategies no longer viable. Consequently, maximizing local PV consumption has become a critical planning objective for high-PV airports.

Existing studies on airport energy systems and park-level integrated energy planning have primarily focused on improving energy efficiency, deploying renewable generation, or optimizing individual storage technologies.[2-6] Most of these articles focus mainly on a few buildings. While battery storage has been widely studied for PV integration, relying solely on electrical storage often leads to high investment costs under high PV penetration.[2,3] Some studies have explored planning and configuration strategies for hybrid energy storage in community energy systems or building clusters.[7-11] However, these studies often do not fully account for the flexibility potential of electric vehicles. Moreover, the source–load characteristics of such scenarios differ significantly from those of major energy hubs such as airports. Several studies have addressed the problem from the perspective of microgrid planning, focusing on optimal capacity configuration and operational reserve allocation under uncertainty.[12-14] While these studies provide valuable insights, they often represent building demand using simplified or aggregated load profiles, without sufficiently capturing the detailed characteristics of building energy consumption, particularly the interactions among electricity, cooling, and heating loads.

For a more refined characterization of demand-side flexibility,[15] developed a probabilistic model to quantify building energy flexibility in real time. In addition, studies such as Refs. [16-17] emphasize the role of demand response and demand-side management within optimization frameworks, providing relatively detailed representations of demand-side responsiveness. Whereas these studies focus on demand response modeling, they mainly focus on individual demand response strategies and do not comprehensively consider the coordinated deployment of multiple flexibility resources.

Meanwhile, airports inherently feature diverse flexible energy resources, including thermal loads, chilled and hot water storage potential, and large

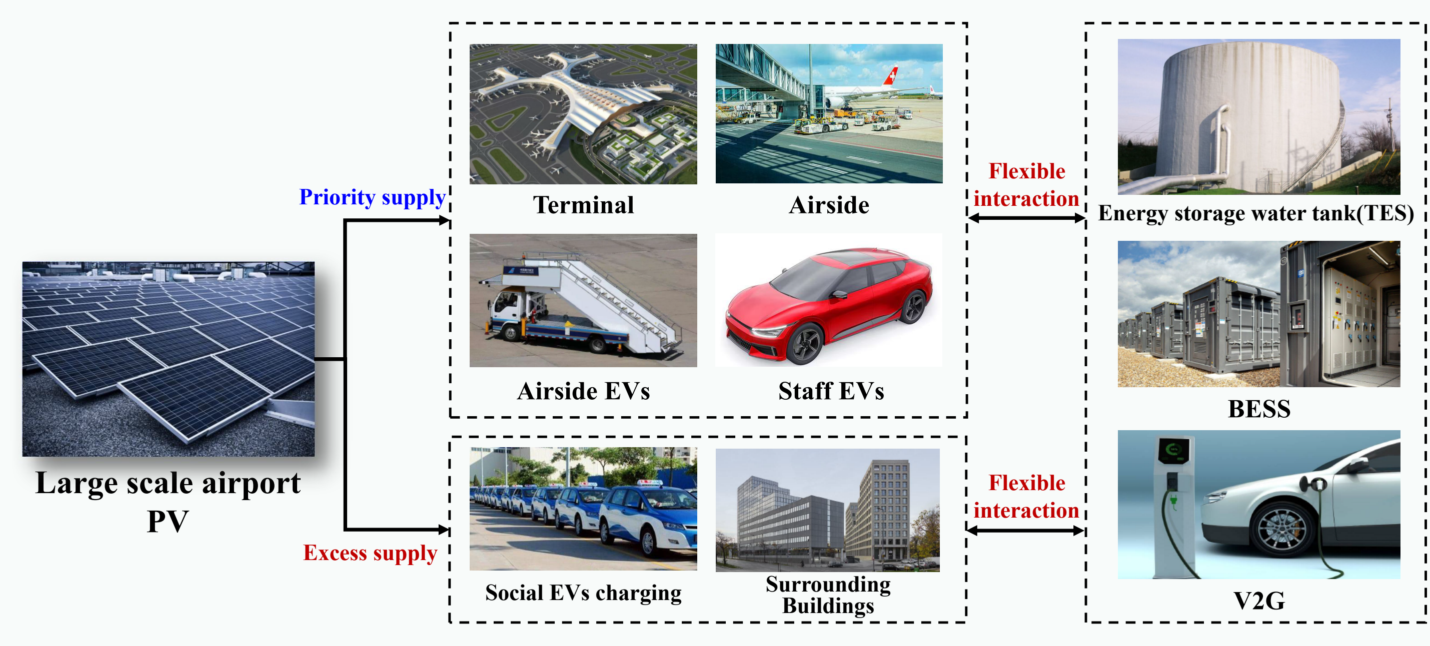

Figure 1. Schematic diagram of energy system planning for the airport

fleets of electric vehicles (EVs) operating on both airside and landside.[18] These resources offer significant but underutilized flexibility for balancing PV generation and demand. Several studies have specifically investigated energy system planning for airports. For example, Ref. 19 examined infrastructure planning for airport microgrids integrating electric aircraft and parking-lot electric vehicles, while Ref. 20 proposed a hydrogen–solar–storage integrated microgrid solution for airport electrification from a techno-economic perspective. Ref. 21 further explored the design and multi-scenario application of airport integrated multi-energy systems. While these studies provide valuable insights into airport energy infrastructure planning, they mainly focus on microgrid design or specific technology pathways, with limited attention to coordinated flexibility planning for high photovoltaic penetration and local PV consumption. In addition, ost previous studies either treat these resources independently or focus on operational scheduling without jointly optimizing system configuration and long-term planning under net-zero constraints.

Beyond internal airport resources, recent studies have also highlighted the potential of integrating external transportation and building systems into energy planning frameworks. For example, Ref. [22] proposed an optimization framework for the long-term planning and operation of coupled electric vehicle and building energy systems, demonstrating that EV fleets can provide valuable flexibility for balancing renewable energy supply and demand. Ref. [23] further reviewed power system planning approaches considering large-scale transportation electrification, emphasizing the growing role of transportation systems as distributed energy resources.

Similarly, coordinated energy management across multiple buildings has been shown to improve overall system performance in urban districts. Ref. [24] investigated the allocation of multiple energy storage resources across different urban forms to enhance techno-environmental-economic performance, while Ref. [25] proposed clustering-based approaches for improving the operational performance of groups of nearly zero-energy buildings. These studies suggest that integrating transportation systems and neighboring buildings can significantly enhance flexibility and renewable energy utilization at the district scale.

However, such perspectives have rarely been incorporated into airport energy planning. Existing airport studies primarily focus on internal microgrid configuration and infrastructure design, with limited consideration of how surrounding transportation systems and nearby buildings may contribute additional flexibility for improving local photovoltaic consumption.[19-21]

To address these gaps, this study proposes a bi-level planning framework for high-PV-penetration airport parks under net-zero carbon development goals. The framework jointly optimizes installed capacities at the planning level and hourly operation at the dispatch level, integrating electricity, cooling, and heating systems with heterogeneous flexible resources, including battery storage, chilled and hot water storage, and uni-directional and bi-directional EV charging. A net-zero carbon constraint is implemented by pricing residual carbon emissions after on-site mitigation through a carbon tax mechanism, with a carbon price fixed at 0.2 CNY/kgCO_2,[26] thereby internalizing environmental costs into the economic optimization. The resulting optimization problem is formulated as a mixed-integer linear programming (MILP) model, which has been widely recognized as an efficient and tractable approach for solving large-scale energy system optimization problems.[27]

The proposed method is applied to a large airport terminal expansion project in China, where planned PV capacity exceeds annual electricity demand. The results reveal how different storage technologies contribute to PV utilization under high penetration and identify characteristic operational patterns driven by PV generation. Furthermore, beyond internal system optimization, this study explores planning strategies that incorporate external resources, such as adjacent buildings and surrounding EV fleets, to further enhance PV consumption and reduce system costs. This planning paradigm fully utilizes the ancillary buildings of the airport and the high traffic flow as a transportation hub, breaking through the limitations of traditional planning.

The contributions of this study are threefold:

(1) It develops a comprehensive bi-level planning framework that captures multi-energy flexibility and net-zero constraints for high-PV airport parks;

(2) It quantitatively reveals the changing roles of electrical and thermal storage under extreme PV penetration;

(3) It demonstrates the effectiveness of external resource integration as a planning strategy to overcome local PV absorption limits.

The findings provide transferable insights for energy planning in airports and other large transport hubs aiming to maximize local PV utilization while achieving economic and carbon performance targets.

MATERIALS AND METHODS

Case description and energy characteristics

Airport terminal expansion case. The case study focuses on the expansion of Terminal 2 at a major international airport in southwestern China, scheduled to be operational by 2030. The planned terminal area exceeds 700,000 m^2, with an annual passenger throughput approaching 100 million. Due to aviation safety constraints, on-site renewable energy options are limited to PV systems. The airport operator plans to deploy PV systems at the maximum feasible capacity of 175.6 MWp across rooftops and open spaces.

Figure 1 shows the overall planning concept, which comprehensively

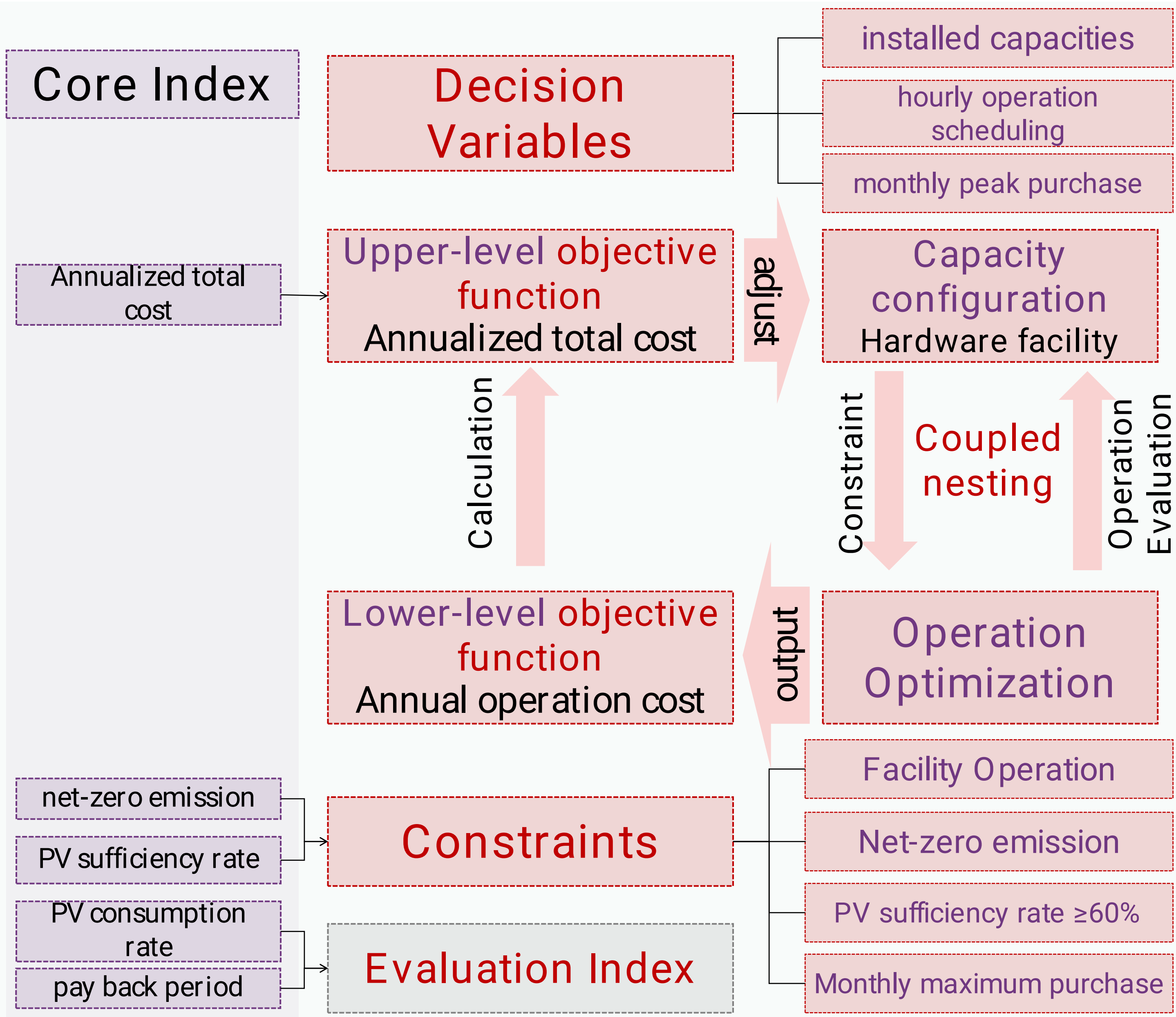

Figure 2. Structure of the bi-level planning framework

utilizes various flexible energy methods and integrates surrounding resources to achieve economically effective utilization of large-scale photovoltaics at the airports.

Load Profile and PV Mismatch. Hourly electricity demand for the new terminal is projected based on historical operational data of the existing T1 terminal area for the whole year of 2023, scaled according to multiple factors including passenger flow, building area, and future electrification level.

The resulting hourly demand profiles across seasons reveal a distinctive pattern in which nighttime electricity demand exceeds daytime demand. Lighting accounts for the largest share of annual electricity consumption, while cooling and heating loads contribute significant seasonal variability. Due to the substantial nighttime lighting demand and the influence of flight schedules, peak electricity consumption during the day generally occurs in the early morning and the first half of the night. This leads to a more pronounced mismatch between airport electricity demand and PV generation compared with typical large public buildings.

Using PVWatts calculator[28] to calculate the annual PV power generation for the whole year, the result shows annual PV generation exceeds total electricity demand, resulting in a baseline PV self-consumption rate of only 33.6% without flexible resources. This extreme PV penetration scenario highlights the necessity of coordinated flexibility planning.

Methodology: Bi-level multi-energy planning framework

Framework overview. A bi-level optimization framework is developed to jointly address planning and operational decisions. Figure 2 shows the framework of the optimization algorithm. The upper level determines installed capacities of energy devices, while the lower level optimizes hourly operation over a full year under given capacities.

The system integrates electricity, cooling, and heating, with flexible resources including: battery energy storage systems (BESS), chilled water storage and hot water storage (collectively referred to as thermal energy storage, TES), uni-directional and bi-directional EV charging infrastructure.

Besides facility operation constraints, a constraint of self-sufficiency rate not less than 60% has been added according to the national zero carbon park standard. And constraints on monthly peak purchasing power are added in accordance with local two-part electricity pricing rules. In addition, a net-zero carbon constraint is imposed through carbon trading as mentioned above.

Upper and lower level objective functions. The upper-level objective minimizes the total annualized cost, including capital investment, electricity purchase costs, and carbon offset expenses. Decision variables include capacities of chillers, electric boilers, storage systems, and EV charging

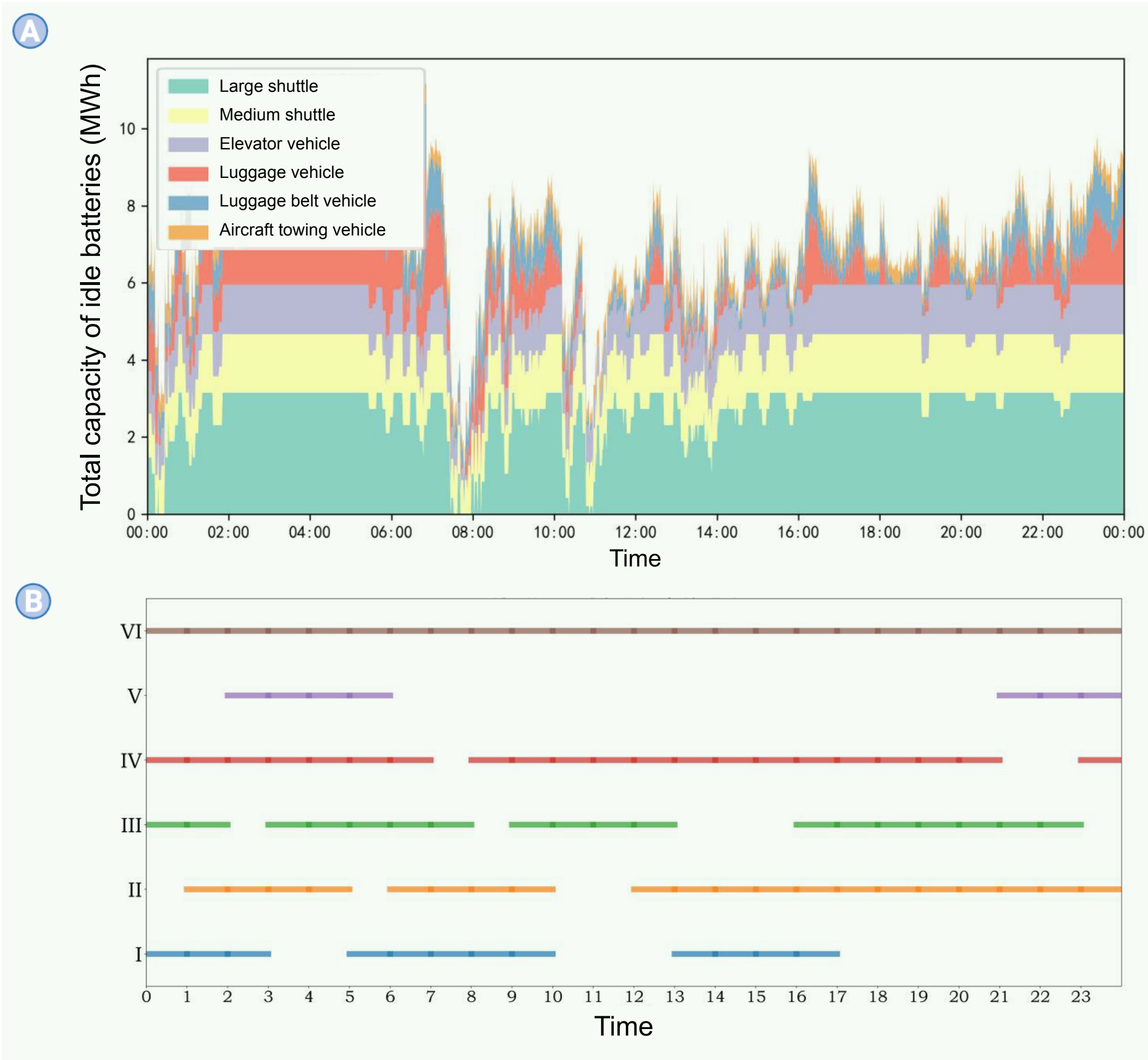

Figure 3. Simulation and Setting of Airside Vehicle Behavior (A) The total amount of idle batteries per minute for vehicles on the airside. (B) Airside EV behavior setting (the solid line represents the time period when the EV groups are connected to chargers)

infrastructure.

The lower level performs hourly dispatch optimization subject to energy balance constraints, storage dynamics, equipment limits, and electricity tariff structures. Thermal storage operation is coordinated with HVAC systems, while EVs are modeled as aggregated flexible storage resources with availability constraints.

Constraints in the Optimization Problem. Firstly, it is necessary to model flexible methods as operational constraints for optimization problems. Taking the refrigeration air conditioner with a cold storage water tank as an example, it can be modeled as Equations 1 to 5.

$$45P_C^{A,t} \cdot COP_C^A + P_C^{r,t} \cdot EER_C^r = P_C^{demand,t} \tag{1}$$

$$46P_C^{x,t} \cdot COP_C^x - P_C^{r,t} \cdot EER_C^r = Q_C^{x,t+1} - Q_C^{x,t} \tag{2}$$

$$0 \leq P_C^{A,t} \leq P_C^{A,max} \tag{3}$$

$$0 \leq P_C^{x,t} \leq P_C^{x,max} \cdot s_C^t \tag{4}$$

$$0 \leq P_C^{r,t} \leq P_C^{r,max} \cdot (1 - s_C^t) \tag{5}$$

where $P_C^{A,t}, P_C^{x,t}, P_C^{r,t}$ are electric power for conventional cooling, cooling storage, and discharge conditions, respectively. $COP_C^A, COP_C^x, EER_C^r$ are the efficiency of these conditions, respectively. $P_C^{demand,t}$ is the demanded cooling load at time t.

The modeling of the air source heat pump coupled with TES and BESS aligns with the aforementioned approach, but exhibits distinct efficiency and COP values.

As for the airside EVs' behaviors, the hourly flight information obtained from the survey for three consecutive days is used. Based on the linkage relationship between airside vehicles and flight arrivals and departures, the operation of the first type of welcome and drop off vehicles was simulated minute by minute, and the typical daily idle battery total of different types of airside vehicles was exported, as shown in Figure 3A. Further grouping the airside vehicles according to different schedules, the schedule for each group of airside vehicles connected to the power grid is shown in Figure 3B, which can meet the same behavior as Figure 3A for all airside vehicles.

For the Uni-directional and Bi-directional EV chargers, simultaneous charging through uni-directional and bi-directional charging piles is modeled as shown in Equations 6 to 8. where $P_{cha,i}^t$ denotes the net charging power of vehicle type i at hour t (negative values indicate discharging), while $P_{cha,i}^{V1G,t}$ and $P_{cha,i}^{V2G,t}$ represent the net charging power through uni-directional and bi-directional charging piles, respectively. $P_{cha}^{V1G,max}$ and $P_{cha}^{V2G,max}$ denote the total installed power capacities of uni-directional and bi-directional charging piles.

$$58P_{cha,i}^t = P_{cha,i}^{V1G,t} + P_{cha,i}^{V2G,t} \tag{6}$$

$$59P_{cha,i}^{V1G,t} \geq 0, \sum_i P_{cha,i}^{V1G,t} \leq P_{cha}^{V1G,max} \tag{7}$$

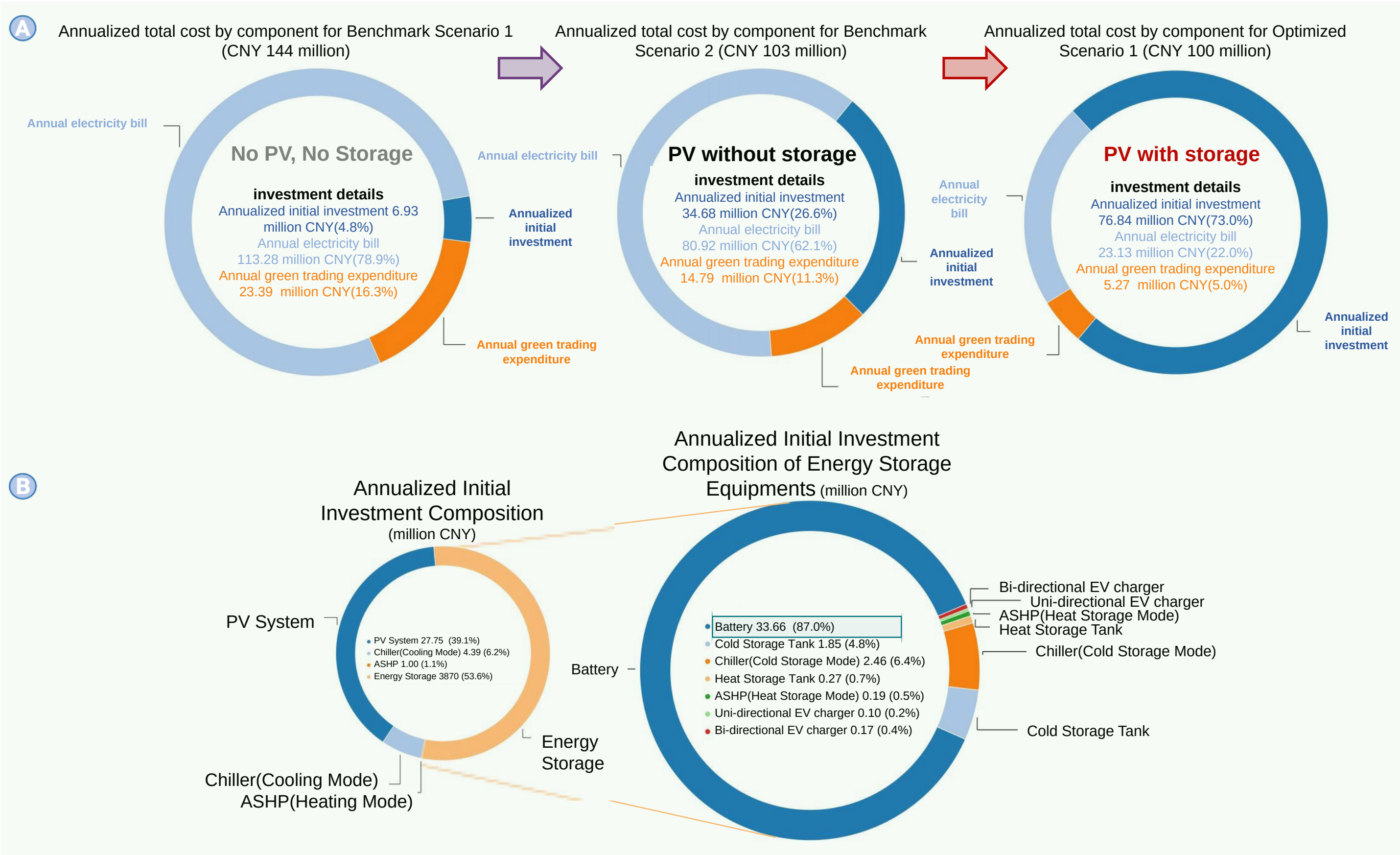

Figure 4. The results of independent planning of the terminal area (A) PV utilization rate and annualized cost comparison. (B) Optimal capacities of flexible resources

$$60\sum_i \left|P^{V2G,t}_{cha,i}\right| \le P^{V2G,max}_{cha} \quad (8)$$

To handle the absolute value term in Eq. (8), which introduces nonlinearity, an auxiliary variable $\overline{P^{V2G}_{cha}}$ is introduced. By enforcing the constraint set in Equations 9 and 10, together with the positive cost coefficient of $P^{V2G,max}_{cha}$ in the objective function, the solution is guaranteed to satisfy the original absolute value constraint in Equations 2 to 9. This approach effectively linearizes the absolute value function.

$$62P^{V2G,t}_{cha,i} \le \overline{P^{V2G}_{cha}} \quad (9)$$

$$-P^{V2G,t}_{cha,i} \le \overline{P^{V2G}_{cha}} \quad (10)$$

Solving Methods for the Optimization Problem. By applying KKT conditional transformation, the lower level optimization problem is equivalently integrated into the upper level problem, thereby achieving the transformation from a bi-level MILP problem to a single-level MILP problem which has 280,356 continuous decision variables, 17,520 binary decision variables and 501,794 constraints. This large-scale single-level MILP problem is solvable by using Gurobi solver. The average solving time is around 10 minutes using a personal computer equipped with an AMD Ryzen 5 4600H processor (6 cores, 12 threads) and 16 GB of memory.

Optimal configuration under high pv penetration. For the independent optimal planning of the terminal area, the PV utilization rate increases from 33.61% to 73.02% after storage installation. As Figure 4A shows, the annualized cost decreases by 33.6% compared with no PV, and by 2.9% compared with PV-only. Indirect carbon emissions drop sharply by 77.46% compared with no PV, and by 64.36% compared with PV-only.

.By analyzing the optimal independent planning scheme for the terminal area, Figure 4B shows that investment in storage power stations accounts for as much as 87%, while chilled and hot water storage serve supplementary roles. As shown in Table S1, the capacities of cold and heat storage are much smaller. Since their economic storage rates rarely exceed 1, their total capacity is limited under high PV penetration.

In contrast, electricity storage faces fewer restrictions and offers more stable charging and discharging, making it more suitable.

MULTI-ENERGY PLANNING RESULTS

Operational characteristics

Taking the fifth week with both cooling and heating loads as a typical case, the operation of the multi-energy flexible microgrid is analyzed. As Figure 5A shows, during the daytime, various flexible resources work together to increase electricity use and consume PV. At night, storage discharges during peak-price hours, while electricity is purchased during flat and valley periods when storage is insufficient. On overcast days, due to limited daytime storage, additional electricity purchase occurs even in the evening peak.

Thermal storage shifts cooling and heating electricity consumption away from PV-scarce hours, while EV charging contributes additional flexibility during idle periods.

Meanwhile, based on the hourly operation data, the annual distribution of curtailed PV is calculated. Figure 5B demonstrates the results, which show that PV curtailment mainly occurs between 10:00 and 17:00, which remains a key challenge for further improvement.

EXTENDED STRATEGIES: EXTERNAL RESOURCE INTEGRATION

Integration of surrounding buildings

The airport group has many supporting office buildings (airlines) and residential buildings (family areas) around the terminal, making it possible for these buildings to work together with the airport for energy planning. Adjacent office and residential buildings are integrated through microgrid coordination. As Figure 6A shows, their load profiles improve source-load matching and reduce internal storage requirements.[29]

EV fleet participation

Staff vehicles and external social EV fleets are incorporated through controlled uni- and bi-directional charging. These mobile storage resources partially substitute stationary battery capacity. Staff EVs are assumed that they park at the airport from 8:00 to 17:00 and connect to chargers in the

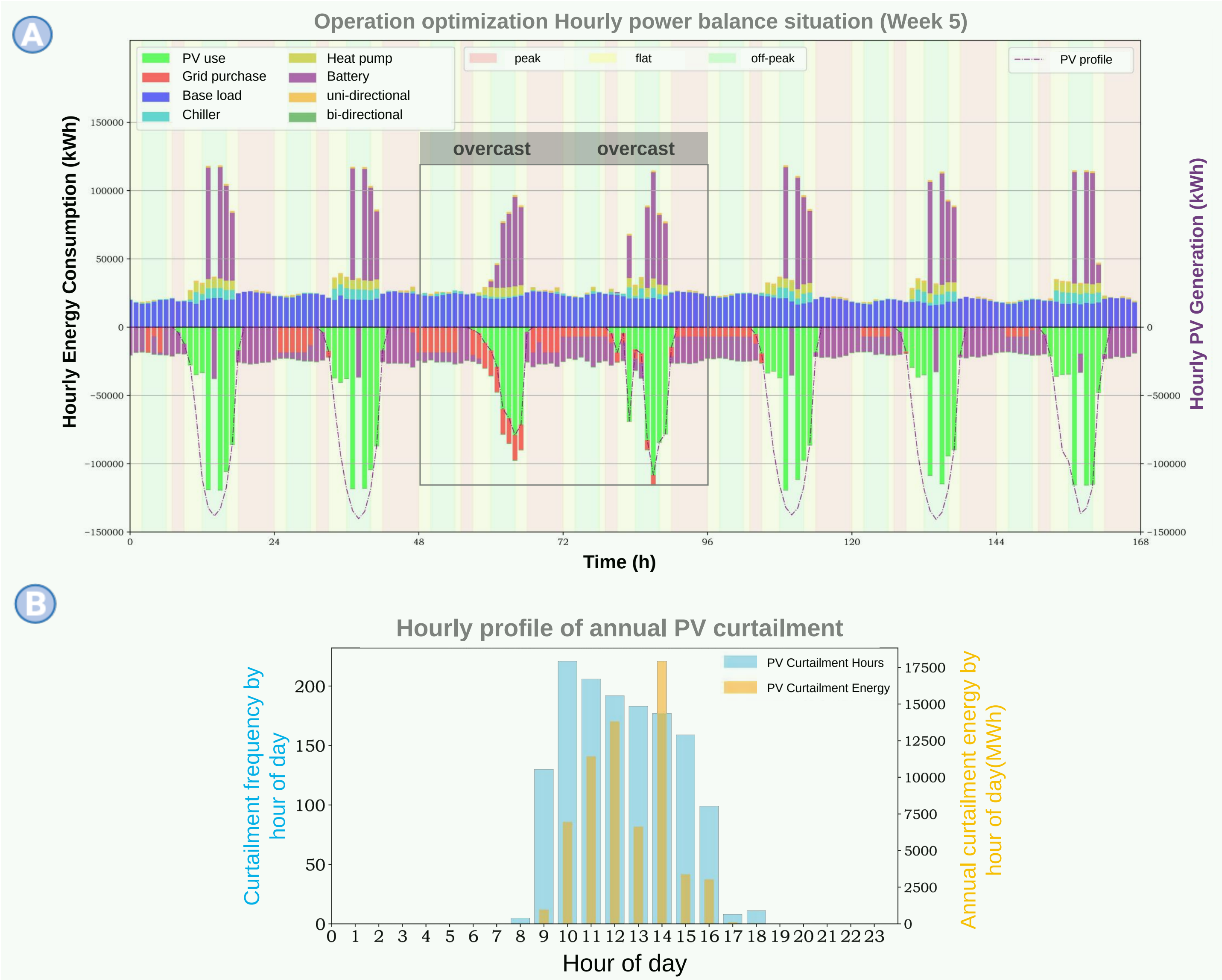

Figure 5. Hourly energy balance and consumption results (A) Optimized scheduling operation results in representative week. (B) Hourly profile of annual PV curtailment under independent planning

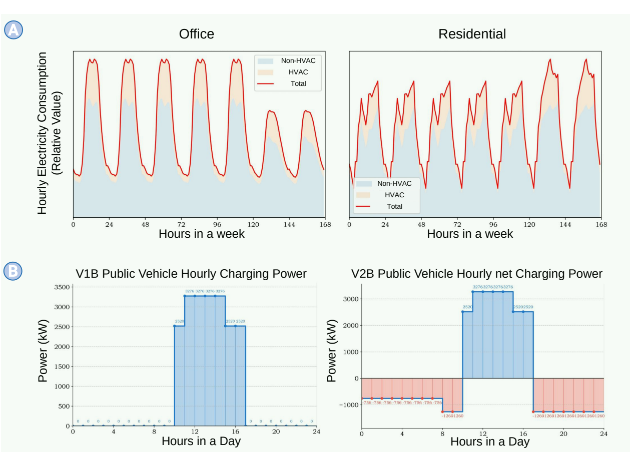

Figure 6. Surrounding Resource Settings (a) Load profiles of surrounding buildings. (b) Net Charge Load profiles of Public Vehicles.

landside parking lot, while park at home from 18:00 to 7:00 next day and connect to chargers in home chargers. Since the residence's grid is connected to airport's, the staff EVs can discharge to the airport power grid at night.[30]

The charging and discharging power of social vehicles is based on the typical hourly distribution obtained from survey, as shown in Figure 6B. The price for providing social vehicle charging services at the airport is set at 0.8 times that of other power stations to attract charging demand.

Scenario analysis

According to the strategy of integrating the surrounding building loads, employee vehicles, and external social vehicles in sequence, eight planning scenarios are set up in sequence, as shown in Table S2.

After integrating surrounding resources, the energy dispatch effect has significantly improved. As shown in Figure 7, for the typical weekly scheduling situation of Scenario VII, compared to Figure 5A, the amount of curtailment PV is significantly reduced. The surrounding buildings have a relatively high proportion of daytime electricity consumption, partially filling the gap of insufficient daytime electricity consumption at the airport. The utilization of employee vehicles significantly increases the power of reverse charging, while social vehicles consume excess photovoltaic energy during the day, which can also bring economic benefits to the airport.

The results of different scenarios across the three stages of resource integration are comprehensively summarized. Annual PV consumption rate and levelized cost of consumed electricity (LCOCE)[31] are used as evaluation metrics.

Figure 8A summarizes the combined effects of integrating surrounding resources. As additional resources are incorporated, the LCOCE decreases from 0.459 CNY/kWh to 0.429 CNY/kWh, corresponding to a 6.5% reduction,

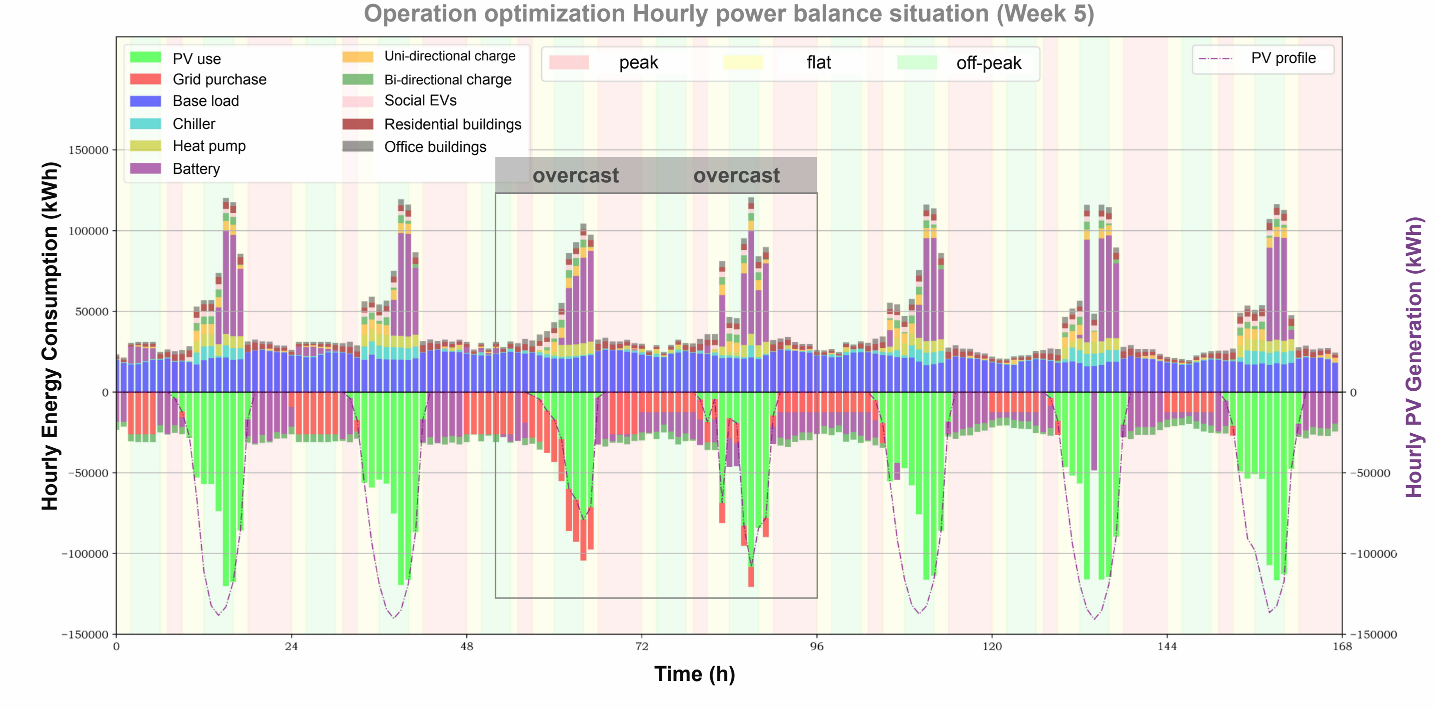

Figure 7. Optimized scheduling operation results in representative week after integrated planning (Scenario VII)

while the PV utilization rate increases from 73% to over 81%, representing an improvement of approximately 12%.

When residential and office buildings are added to achieve aggregate capacity matching, overall self-sufficiency and PV utilization improve; however, total annualized cost increases. This is mainly because these buildings do not share chilled and hot water storage with the airport and lack dedicated thermal storage, leading to higher standalone cooling and heating costs. After incorporating all absorbable surrounding buildings, the park-level LCOCE still decreases, indicating that the benefits of improved source–load matching outweigh the efficiency losses from independent thermal operation.

These results suggest that the economic performance of park-level integration depends on the optimal scale of surrounding building absorption, as adding arbitrary building areas does not necessarily improve profitability. In addition, although subsidized discharging of staff vehicles yields the highest PV utilization, higher storage investment prevents this scenario from achieving the best economic performance.

Figure 8B presents a comparative analysis of the optimal configuration of flexible storage devices under different resource integration scenarios. Storage capacities are normalized by annual electricity consumption to ensure comparability. The results show that, as surrounding building and transportation resources are incorporated, the required capacities of battery storage, chilled water storage, and hot water storage all exhibit decreasing trends. This indicates that the integration of external resources effectively mitigates source–load mismatches and reduces the demand for internal storage deployment.

Among these resources, battery storage shows the most pronounced reduction, particularly after the integration of staff and public EVs, which directly substitute part of the stationary battery capacity. In addition, with the increasing participation of staff and public EVs in vehicle-to-building (V2B) operation, the installed capacities of uni-directional and bi-directional charging piles continue to increase.

Calculating the baseline PV utilization and self-sufficiency for each scenario, Table S3 suggest that optimizing the integration of surrounding buildings improves generation-load matching, increases both baseline utilization and self-sufficiency, and thus reduces the demand for flexible storage devices.

CONCLUSIONS AND IMPLICATIONS

This study presents a bi-level planning framework for high-PV-penetration airport parks under net-zero development goals. Results demonstrate that internal multi-energy flexibility can significantly enhance local PV consumption and reduce costs, with battery storage playing a dominant role under extreme PV penetration. Thermal storage and EV flexibility provide complementary benefits.

Beyond internal optimization, integrating surrounding buildings and EV fleets further improves PV utilization and economic performance. These findings indicate that high-PV airport parks require both internal multi-energy coordination and external resource integration to overcome local PV absorption limits.

The proposed framework and insights are transferable to other transport hubs and large urban districts seeking to maximize local PV consumption while achieving carbon neutrality under policy constraints.

However, several limitations should be acknowledged. First, the analysis is based on a single airport case study, and although the modeling framework is generalizable, the quantitative results may vary under different climatic conditions, electricity price structures, and airport operational characteristics. Second, the study assumes simplified operational behaviors for external resources such as electric vehicles and surrounding buildings, while real-world participation may be influenced by user behavior, market incentives, and infrastructure constraints. Third, uncertainties in future technology costs, carbon pricing, and policy environments are not explicitly modeled.

Future research could address these limitations by incorporating stochastic modeling of renewable generation and demand uncertainties, exploring dynamic pricing or market-based mechanisms for coordinating external flexibility resources, and extending the framework to multi-park or district-scale energy systems. Such developments would further improve the robustness and practical applicability of planning strategies for high-renewable energy infrastructure systems.

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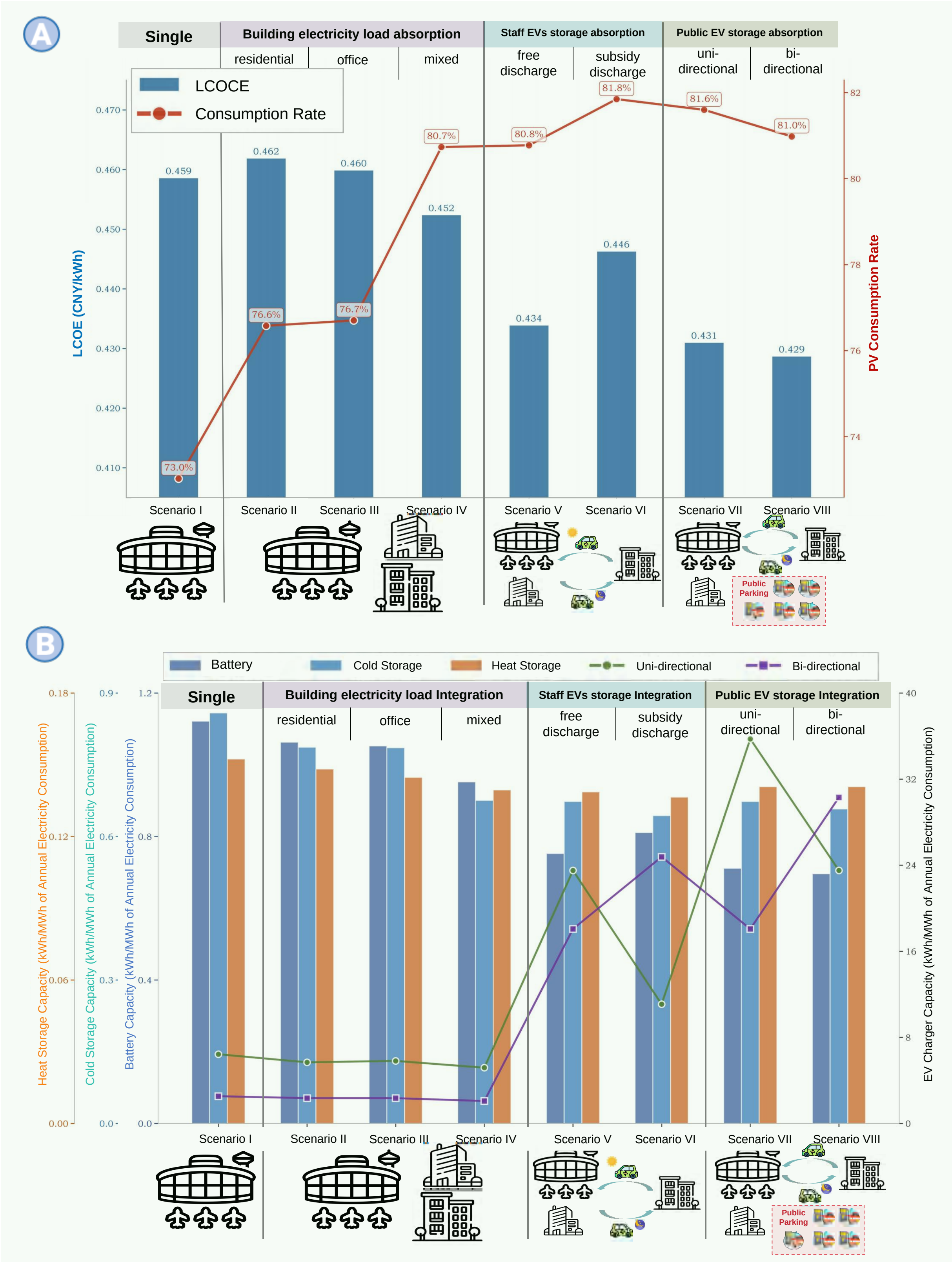

Figure 8. Summary of the planning results of scenarios (A) Optimal LCOCE and PV consumption rate in different scenarios. (B) Unit capacity of storage equipments in different scenarios.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

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