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Pathway for Airports to Net-Zero Carbon Emissions

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Airports are critical infrastructure and prominent landmarks in our society. Decarbonizing airports has demonstrative significance for sustainable development but remains challenging, given that they serve as a critical nexus of transportation, building, and energy systems with substantial carbon emissions. This paper clarifies the carbon footprints of airports and explores a feasible pathway to net-zero carbon emissions: full and safe integration of renewable energy sources, electrification–energy saving–flexibility utilization of end-users, and human-centric and carbon-aware intelligent control of energy systems. For energy supply, on-site photovoltaic (PV) and ground-/water-/air-sources heat pump systems are increasingly practiced, particularly focusing on safety issues. For energy demand, tapping into the energy storage potential of ground electric vehicles (EVs) and heating, ventilation, and air-conditioning (HVAC) systems is a promising approach to balancing the energy supply–demand mismatch. Finally, Taiyuan Wusu International Airport is introduced to illustrate the decarbonization pathway, outlining the emerging opportunities of sustainable airports worldwide.

DEFINITION AND PATHWAY FOR NET-ZERO-CARBON AIRPORTS

Carbon footprint clarification. Based on the Greenhouse Gas Protocol and ISO 14064, carbon emissions of an airport are generally categorized into three scopes, as shown in Figure 1. Scopes 1 and 2 emissions fall under the direct control of the airport, mainly depending on the energy use of owned stationary (e.g., terminal buildings) and mobile (e.g., ground vehicles); however, Scope 3 emissions are outside of its direct control, relating to activities of third-party users (e.g., airlines, tenants, and passengers). To assess airports' efforts on managing carbon emissions, Airports Council International EUROPE launched Airport Carbon Accreditation in 2009, which requires the topmost level of zero-carbon airports to maintain a net zero balance on Scopes 1 and 2 and actively address Scope 3 emissions (e.g., strengthening third-party engagement and offset removals for residual emissions). This definition of net-zero-carbon airports has been increasingly adopted by airports in Europe, the Asia-Pacific region, Africa, and the Americas. Until June 2025, 314 airports across 36 European countries have committed to achieving and maintaining net-zero carbon emissions from operations within their control by 2050 at the latest. In the context of China's goal to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 ("Dual Carbon"), China has outlined a primary plan for the green development of civil aviation and launched a continuous evaluation of "Dual Carbon Airports" for comprehensive carbon management.

Pathway to net-zero-carbon airports. Mapping an airport's carbon footprint paves the way for its decarbonization, which is achieved chiefly through the low-carbon transition of its energy system,¹ as illustrated in Figure 1. First, the direct emissions under the airport's control need to be nearly eliminated by comprehensive electrification and clean fuel switching (Scope 1), particularly for the fossil fuel use in HVAC systems and ground support

equipment (mainly ground vehicles). Second, the electrified energy system needs to be decarbonized through demand-side energy saving, supply-side renewable integration, and energy storage/flexibility utilization with intelligent control (Scope 2), aiming at reducing carbon emissions from its own operation to the greatest extent. Third, the remaining emissions that are difficult to reduce need to be further neutralized through carbon removal or storage (Scope 3). The following sections will discuss applications and perspectives of the key technologies in this pathway.

FULL AND SAFE INTEGRATION OF RENEWABLE ENERGY SOURCES

The deployment of renewable energy sources at airports is tailored to local conditions. The balance between their potential exploitation and associated safety risk control is of paramount importance.

Power sources. PV systems represent the most potential and economical on-site renewable power source currently at airports,² due to the expansive lands and unobstructed building surfaces. Fine design and operational management of PV panels and systems can mitigate their risks, including glares caused by reflections from panels, electromagnetic interference caused by converters, and detachment of PV parts due to winds, vibrations, aircraft wakes, etc. Many airports worldwide have deployed or plan to deploy large-scale on-site PV systems. Their capacities can be benchmarked using the ratio of installed capacity to annual passenger throughput (W_p /passenger), such as 1.08 of Cochin International Airport in India (2024), 1.42 of Vienna International Airport in Austria (2024), 1.66 of Indianapolis International Airport in the USA (2024), 2.40 of Narita International Airport in Japan (2045), and 2.71 of Taiyuan Wusu International Airport in China (2035)¹. While the open expanses of airports also present a potential for wind power generation, its large-scale on-site deployment is hindered by aviation constraints, including concerns over physical obstruction, radar interference, and wake turbulence. Off-site renewable power sources, like dedicated wind or solar farms, offer a broader range of options, as they do not face the same stringent safety constraints as on-site installations.

Heat sources and sinks. Beyond direct methods like solar thermal heating and natural ventilation cooling, advancements in heat pump technologies facilitate the utilization of a broader spectrum of renewable thermal resources. The availability of ample lands makes airports well-suited for geothermal energy systems, primarily utilizing borehole heat exchangers (BHEs).¹ For shallow geothermal systems reaching 50–200 m underground, Beijing Daxing International Airport in China deployed 10,497 BHEs, as the largest-known system at airports.³ Their main challenge lies in mitigating thermal imbalance between heat extraction and dissipation. The application of mid-deep geothermal energy, using BHEs that reach 2–3 km underground to extract heat at 50–100 °C, has been investigated at Chinese airports for direct/indirect heating, e.g., Xi'an Xianyang, Changsha Huanghua, and Lanzhou Zhongchuan International Airports. Its challenges include high capi-

Pathway for airports to net-zero carbon emissions

A. Carbon emissions at an airport

- Scope 1** Direct emissions from airport-owned or airport-controlled sources: Ground support equipment (GSE), generators, boilers, waste management, etc.
- Scope 2** Indirect emissions from the consumption of purchased energy: Electricity, heating and cooling (H&C), etc.
- Scope 3** Indirect emissions from other sources related to the airport activities: Flights, auxiliary power units (APU), passengers, tenants, staff, etc.

B. Decarbonization pathway for Taiyuan Wusu International Airport

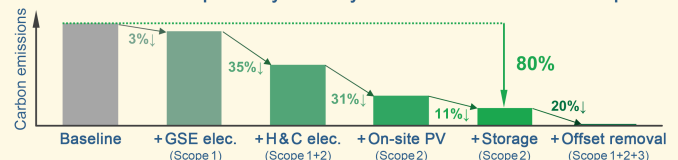


Figure 1. Pathway and technologies for airports to achieve net-zero carbon emissions.

tal cost and uncertain stability of long-term operation. Water-source heat pumps are beneficial, but geographical constraints and biofouling-induced performance degradation limit their wide use. Applications include lake water-source heat pumps in Nashville International Airport in the USA and seawater-source heat pumps in Chubu Centair International Airport in Japan. Some special natural sources for heating or cooling are also reported being used at airports, such as radiative cooling for heat dissipation to outer space at Singapore Changi International Airport and stored snow for cooling at Oslo Airport in Norway.

Clean fuels. Biomass energy, derived from forestry/agricultural wastes or on-site sources, is utilized in limited yet feasible airport applications for heating and power, particularly in cold regions like the UK, Sweden, and Finland.¹ Hydrogen is gaining attention due to its potential as an aviation fuel and long-term storage.⁴ Nevertheless, its large-scale adoption is hindered by significant costs and low round-trip efficiency.

ELECTRIFICATION, ENERGY SAVING, AND FLEXIBILITY UTILIZATION OF END-USERS

The decarbonization of airport energy end-uses can be structured into three key steps: (1) Electrification to eliminate direct emissions; (2) Energy saving to reduce overall demand; (3) utilization of demand flexibility to accommodate renewable generation.

Terminal buildings and HVAC systems. Terminal buildings are an airport's largest energy end-user (over 70% of the total consumption), in which HVAC systems are the primary driver, responsible for 40%–80%. Given the high electrification rate of modern terminal buildings, energy saving of HVAC systems is a fundamental step towards decarbonization. Terminal buildings feature large spaces with highly glazed facades and various openings. For lighting environments, shading systems and advanced facades (e.g., electrochromic glass) enable adaptive control of sunlight and heat entering

indoors, improving energy efficiency and enhancing occupant comfort¹. For thermal environments, studies on large-space buildings have shown that radiant floors with displacement ventilation create a vertically uniform indoor thermal environment when heating and an effectively stratified one when cooling, thereby minimizing energy demand.⁵ By integrating this system with low-temperature heating and high-temperature cooling, a novel thermal and humidity independent control system was developed, which was applied at Xi'an Xianyang and Qingdao Jiaodong International Airports in China, saving 20%–40% of HVAC energy use. Furthermore, HVAC systems represent substantial demand flexibility through inherent energy storage resources, encompassing water/ice storage, network thermal inertia, and building thermal mass. Empirical data from two Chinese hub airports confirm their potential, with a load shed potential of 2–15 MW for durations of 6–20 h.⁶

Ground support equipment (mainly ground vehicles). The current EV industry has established a comprehensive product system to meet most of the needs at airports, making electrifying ground vehicles a worldwide consensus for airport decarbonization. The main types of ground vehicles at an airport include airside and landside vehicles. Airside vehicles are owned by the airport or airline companies and strictly managed. The electrification rate of these vehicles has been significantly higher than that of social vehicles, especially for newly built airports in recent years, e.g., 79% at Beijing Daxing International Airport and 74% at Chengdu Tianfu International Airport in China. Landside vehicles serve passengers traveling to or leaving the airport (e.g., private vehicles, taxis, and buses) or serve airport staff (e.g., employees' private vehicles and company vehicles). In addition to reducing direct emissions, EVs can also provide significant energy flexibility through vehicle-to-grid (V2G) technologies. An investigation into a Chinese hub airport's vehicle fleets quantified their V2G potential nearly sufficient to meet the energy storage demand of a fully PV-supplied airport.⁷ Furthermore, the ongoing trend toward aviation electrification is fostering the integration of electric aircraft

into airport energy systems, which can similarly leverage the V2G framework to enable supportive energy interaction.⁴

HUMAN-CENTRIC AND CARBON-AWARE INTELLIGENT CONTROL OF ENERGY SYSTEMS

Complex airport energy systems with various supply-side and demand-side resources necessitate intelligent control technologies to adapt to the needs of indoor human and decarbonization.

Dynamic passenger flows distinguish airport terminals from conventional public buildings. Accurately predicting them to guide indoor environment control is key to enabling energy-efficient operation and occupant-centric service quality,⁸ e.g., ventilation control based on flight arrangement and indoor CO₂ concentration, indoor lighting control based on passenger flow videos, and indoor temperature control based on human infrared thermal imaging. Furthermore, field surveys in airport terminals have shown diverse preferences for the indoor environment among different groups of people (passengers, staff, etc.) and in different indoor zones (check-in hall, departure lounge, etc.).¹ This feature requires sophisticated control solutions that merge comprehensive spatial perception with adaptive zone-level regulation.

Decarbonized airport energy systems, subject to highly dynamic inputs like weather, on-site generation, passenger flow, and electricity/carbon tariffs, require advanced control methods. Data-driven machine learning algorithms are increasingly employed, e.g., optimal dispatch of electricity-thermal-hydrogen airport microgrids,⁴ model predictive control of chilled water systems,⁸ field knowledge-informed reinforcement learning for synergistic control of active and passive thermal storage in HVAC systems.⁹ Nevertheless, the field's progress is limited by a dependence on simulations that inadequately represent real-world conditions. Future work must prioritize real-world implementation and develop integrated control frameworks that coordinate supply with demand to fully unlock the system flexibility for low-carbon operation.

Future perspectives, an example of Taiyuan Wusu International Airport

Taiyuan Wusu International Airport (TWIA) in China set an ambitious target to achieve net-zero carbon emissions in operation by comprehensively shifting to renewable energy.¹⁰ It features a smart microgrid coordinating 108.5 MW_p on-site PV, high-efficiency heat pumps with 28 mid-deep geothermal BHEs, over 17 MWh stationary batteries, about 200 bidirectional EV chargers (V2G), 34,000 m³ cold/hot water storage tanks, and other power loads. The annual PV generation can exceed 100 million kWh, enough to cover the TWIA's total power demand. The multi-type energy storage system aims to enhance the self-consumption of the on-site PV generation, helping to achieve net-zero carbon emissions. Towards the 2035 scenario with 40 million passengers annually, TWIA's pathway to a net-zero-carbon airport is illustrated in Figure 1. TWIA is a prime example of transforming a conventional carbon-intensive hub airport into a net-zero-carbon one, which is

expected to generate valuable practical experiences that can guide other airports in their pursuit of decarbonization.

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AUTHOR CONTRIBUTIONS

Xiaochen Liu: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Visualization, Writing - original draft. **Yang Chen:** Conceptualization, Resources, Funding acquisition, Project administration, Writing - review & editing. **Jiagen Liu:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing. **Ziyi Luo:** Data curation, Formal analysis, Investigation. **Tao Zhang:** Conceptualization, Funding acquisition. **Xiaohua Liu:** Conceptualization, Resources, Funding acquisition, Supervision, Writing - review & editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.