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Innovative Pathways for Green Carbon Neutrality in Civil Aviation Airports under Carbon Constraints

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Abstract

As climate change issues were the focus of this generation, the aviation sector was under pressure to decarbonize, such as from long-haul flights and airport operations. This research investigated Beijing Daxing International Airport (PKX) as a pioneering example of green airport development in the context of China's "Dual Carbon" goals (2030/2060). The study examined PKX's integration of geothermal energy, sustainable terminal design, and transportation systems to address its accomplishments in terms of carbon neutrality. A mixed-methods, including quantitative energy data analysis, comparative global case studies, and policy evaluation demonstrated the replicability of PKX's model. The improvements of the recommended policies included unifying green certifications, incentivizing sustainable aviation fuel (SAF), and enforcing transparent carbon disclosure to support the aviation industry's transition toward sustainability and environmental justice.

Keywords

Green Airports; Carbon Neutrality; SAF; Renewable Energy; Policy Frameworks.

1. Introduction

1.1. Global Aviation Emissions and Environmental Challenges

As the urgency of global warming continues to mount, The interconnection between energy consumption from all industries, such as the aviation sector and environmental degradation is becoming more evident. Long-haul flights (>1,500 km) dominate aviation emissions (80%), while airport operations account for 10–15% of sectoral CO2, primarily from ground support equipment (GSE) and heating/cooling systems [1]. The International Civil Aviation Organization (ICAO) emphasizes systemic reforms, including sustainable aviation fuels (SAF), operational efficiency improvements, and carbon offset mechanisms (e.g., CORSIA), to achieve net zero by 2050. Hence, SAF was well-advised to be utilized for life-cycle emissions reduction by 80% compared to conventional jet fuel, though production costs remain prohibitive [2]. With the growth of air travel, especially in emerging markets such as China and India, the environmental impact of the aviation industry is expected to surge further. Hence, the aviation industry is under pressure to decarbonize, and the environmental challenge and corresponding and innovative strategies will be examined in further detail. Specifically, as China has already become the world's second-largest national air travel market, energy consumption and aviation emissions would be the focus of discussion and analysis in the environmental justice context [3].

1.2. China's Dual Carbon Strategy and Aviation Policy

The following initiatives reflected China's broader ambition in decarbonization efforts through the aviation sector and air travel market policies in energy transition in airports and aviation and green technology innovation. For instance, China's 2030/2060 "Dual Carbon" goals

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mandate 25% electrification of airport ground vehicles by 2025 and SAF adoption trials in major hubs [4]. Admittedly, some airports, such as Beijing Daxing International Airport (IATA: PKX) exemplify progress through its shallow geothermal system, which reduced 4.05 million tons of CO2 from 2020–2023, and solar PV projects generating 10 million kilowatt-hours (kWh) annually. However, other regional disparities persist and await optimal strategies and policy support to improve the situations; for example, airports in western China lag in electrification due to grid instability [5] and the international carbon pricing for aviation was not uniformly regulated [6].

1.3. Strategic Role of Beijing Daxing International Airport

As a national green benchmark, PKX integrates LEED Platinum-certified architecture, transit-oriented development (TOD) principles, and a "sponge airport" design to manage rainwater runoff to tightly align with the Sustainable Development Goals (SDGs). Specifically, the terminal enhanced efficiency and reduced energy consumption through natural lighting design and the integrated transportation system. Likewise, the sponge infrastructure captures 85% of stormwater, irrigating 600000 m^3 annually while mitigating urban flooding [7]. Hence, with an annual passenger capacity of 72 million, PKX served as a testbed and paragon for implementing scalable decarbonization strategies PKX would be a case study in this research to illustrate the carbon neutrality process in civil aviation airports.

1.4. Research Questions and Methodology

This study addressed the following research questions:

1) How could PKX's green innovations be replicated globally?

2) What policy barriers hinder standardized decarbonization?

The methodology combined three approaches to more comprehensively evaluate the research questions by balancing the pros and cons of different approaches:

1) Quantitative analysis: Energy consumption data from PKX's smart grids (2019–2024) and CO2 footprint modelling using the ICAO Carbon Emissions Calculator. The quantitative approach could collect quantitative evidence in order to create changes in policies through data analysis and the benefits of this approach included a larger sample without a longer time for data collection [8].

2) Qualitative analysis: Comparative case studies of Schiphol (Netherlands) and Changi (Singapore), focusing on SAF adoption and multimodal integration. The qualitative approach was applied to elicit deeper insights by comparing Schiphol Airport (Netherlands) and Changi Airport (Singapore) with PKX to highlight their respective strengths and weaknesses draw lessons from best practices, and identify areas for improvement [8].

3) Policy analysis: As the focus of this study was on green aviation and carbon neutrality, thus the evaluation of alignment with ICAO's CORSIA and China's 14th Five-Year Plan would be significant to serve as both global and China-specific guiding roles.

2. Carbon Neutrality Progress and Emission Reduction Measures at PKX

2.1. Major Carbon Emission Sources and Mitigation Strategies

Table 1 included PKX's primary carbon emissions sources:

Table 1. PKX Emissions Breakdown (2023)

Source	Contribution (%)	Mitigation Strategy
Aircraft	80	Optimized flight paths
Ground vehicles	12	Electrification
Heating, Ventilation, and Air Conditioning (HVAC)	8	Geothermal energy

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First, aircraft operations accounted for 80% of the carbon emissions, thus the mitigation strategies for this source were of paramount importance. For instance, according to Skybrary (2025), "A reduced thrust takeoff is a takeoff that is accomplished utilising less thrust than the engines are capable of producing under the existing conditions of temperature and pressure altitude [9]. Hence, via "reduced-thrust takeoff" protocols, the main benefits were saving costs by extending engine lifespan and lowering overhaul expenses with additional reduced noise to align with environmental justice [9]. Moreover, route optimization would also be the focus to be solved through route planning optimization, such as direct routing, AI-driven predictive routing to avoid severe convection and dynamic airspace management.

In addition, ground vehicles accounted for 12% of the total emissions, yet the 79.19% electrification rate by 2023 has exceeded China's 2025 target where nearly 8 out of every 10 such vehicles were electric. This early achievement reflected a strong commitment to decarbonization and highlighted the rapid progress in adopting green airport technology and managerial innovation [10].

The HVAC systems also occupied 8% of the emissions, and the geothermal energy reduced the total heating and cooling energy demand: Heat Pump systems saved up to 51% of electricity consumption in HVAC in general and specifically the HVAC system of PKX had the largest Ground Source Heat Pump system in China where providing cooling, heating and ice storage to the airport at different seasons [11].

2.2. Comparative Analysis with Global Airports

In the global north, Schiphol Airport in the Netherlands has achieved that sustainable taxiing reduced fuel consumption by 50% and decreased emissions of CO2 [12]. For instance, between 2022 and 2024, the airport subsidized the additional costs of SAF, leading to the use of over 40,000 tons by participating airlines. However, SAF currently accounts for only 1% to 2% of the total fuel used at Schiphol, primarily due to higher costs and limited availability [13]. Likewise, San Francisco International Airport in the USA also targeted net-zero by 2030 via SAF subsidies ($1.5/gallon) to reduce greenhouse gas emissions by up to 80% over the fuel's lifecycle compared to conventional jet fuel [14, 15]. On the contrary in the global south, Indira Gandhi International Airport in India achieved carbon-neutral certificates through 48 megawatts (MW) solar installations but still relied on carbon offsetting, such as afforestation due to low SAF adoption and supply chain challenges. However, India has great potential to produce SAF in the future using available biomass waste and feedstocks like rice and wheat straws [16].

2.3. Policy and Transparency Gaps

PKX lacks a publicized CN timeline, yet its alignment with China's "1+N" policy framework where '1' represents the overall goal of peaking carbon emissions and achieving carbon neutrality by 2030/2060, while 'N' represents the supporting implementation plans for various industries and regions to ensure compliance with carbon trading systems (CCER). However, transparency remained a challenge where only 34% of global airports disclose Scope 3 emissions (indirect carbon emissions related to airport operations, such as passenger travel, airline fuel use, and supply chain transportation). Even globally, most airports have not yet achieved comprehensive information disclosure, with the tightening of carbon regulations, this would become an important direction for countries or benchmark airports like PKX to enhance international influence and competitiveness [17].

3. Green Building Design and Energy Systems

3.1. Architectural Innovations

PKX's terminal employed eco-friendly architectural design and intelligent energy systems to enhance overall sustainability, including natural ventilation and smart lighting systems. Natural

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ventilation was the seasonal airflow system where, in spring and fall, instead of using air conditioning or heating, the terminal utilized natural outdoor airflow to maintain a comfortable temperature within the terminal, which reduced HVAC loads by 15%, saving 3.2 gigawatt-hours per year (GWh/year) [18]. Likewise, smart lighting was an AI-driven adaptive control, which adjusted brightness based on occupancy and daylight, also reducing energy use by 18% [18]. Notably, during the daytime especially during sunny daytime hours, the glass ceiling was translucent at the terminal of PKX for absorbing ample natural lighting, making lights unnecessary to further save electricity and energy.

3.2. Renewable Energy Integration

PKX installed solar PV panels on its large parking lot grounds, with an installed capacity of 12 MW. The installations harness solar energy to generate about 3 million kWh of power per year. The clean power generated is used to power lights, charging stations, and ventilation systems at the parking facilities, primarily sparing grid-supplied energy use and carbon emissions. In addition to terminal roof transparency, the parking facility was also equipped with roof-top solar panels supplying renewable electricity to the building systems directly, as part of the airport's carbon reduction and green building objectives.

4. Sustainable Transportation Systems

4.1. Multimodal Connectivity

Some airports were far away from the downtown of a city, and more passengers preferred to not take public transportation than their counterparts of private cars or taxis. PKX integrated high-speed rail (20-minute downtown access), metro lines, and EV charging hubs (245 stations) to attract more people to take public transportation or eco-friendly vehicles to achieve sustainable transportation systems with higher transfer efficiency via the transportation systems in the terminal. Specifically, trains are particularly low-carbon ways to travel, and it is not public transportation, driving an electric vehicle (EV) was the best mode of private transport [19].

5. Policy Recommendations

5.1. Limitations and Replicability Challenges

This research focused on the PKX as an example to illustrate the progress of carbon neutrality in the aviation industry. However, the limitation included the generalizability of the PKX Model because it benefited from design, technology, national political position and financial support which might not be applicable in other smaller regional airports and the majority of developing countries. Furthermore, the current policy might evolve and not consist of global aviation policy, thus the actual enforcement or market response may shift when the policy develops dynamically. Hence, the policy analysis component is inherently limited. Notably, PKX was relatively a new airport which might not include a complete Lifecycle Assessment (LCA) for construction materials and plane manufacturing data to verify their long-term reliability and maintenance costs. Omitting this long-term cost analysis would limit the evaluation of the airport's true carbon footprint in long-term sustainability. For instance, high upfront costs hindered scalability because geothermal systems required 25 million/km^2 while SAF production costs exceeded 1,200/ton [20]. Therefore, the possibilities for replicating PKX's decarbonization trajectory globally were also constrained by regional policy, environmental and economic factors.

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5.2. Actionable Strategies

To optimally correspond these issues for green aviation innovation from the policy recommendation perspective, three strategies were specified. Unify green certification schemes, such as Airport Carbon Accreditation (ACA) and Leadership in Energy and Environmental Design (LEED) to simplify compliance for multinational operators and easier benchmarking and policy implementation. Currently, SAF lacks enough incentives because of the higher prices. Nonetheless, the European Union has requested the use of 6% SAF (ReFuelEU) by 2030, which has a leading impact on the global aviation industry and market. Hence, the Production Tax Credit of SAF would be an ideal policy incentive for further innovation and implementation. Lastly, a more accurate carbon disclosure was awaited to be revealed through setting up the carbon reporting system with monitoring and penalties, which could better evaluate the emission reduction effectiveness of the aviation chain through unified and transparent carbon emission data.

6. Conclusion

Green carbon neutrality in civil aviation airports was in positive progress, such as PKX demonstrating the viability of systemic green innovation: ranging from geothermal HVAC systems to multimodal transport hubs and LEED-certified architecture, positioning it as a national benchmark for low-carbon aviation. Nevertheless, global replication demanded context-specific adaptations from cost, policy inconsistencies, and infrastructural disparities, particularly in developing regions. PKX has emerged as a pioneering model for achieving carbon neutrality in the global aviation sector, demonstrating the viability of systemic green innovation through its integrated approach to energy, infrastructure, and operational efficiency. By leveraging shallow geothermal systems, achieving 79.19% electrification of ground vehicles, and adopting AI-driven smart grids, PKX has validated the technical and economic feasibility of large-scale decarbonization in aviation infrastructure. However, the global replication of the "Daxing Model" requires context-specific adaptations to address regional disparities in resource availability, policy frameworks, and technological readiness.

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