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A Study on the Measurement and Prediction of Airport Carbon Emissions Under the Perspective of Carbon Peak †

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Abstract: Against the dual-carbon background, civil aviation is in urgent need of low-carbon and green transformation. Carbon emissions from airports are one of the main environmental concerns in civil aviation, so the early realization of airport carbon peak and carbon neutrality will help accelerate the construction of green civil aviation and assist in the low-carbon transformation and upgrading of civil aviation. According to research, the terminal building, aircraft, and ramp area are the main sources of airport carbon emissions. Taking Harbin Taiping International Airport as an example, this study first measured the carbon emissions from the terminal building and ramp area of the airport in the past five years by using the emission factor method; then, we measured the carbon emissions from aircraft in the airport in the past five years by using the ICAO method and finally predicted the trend of carbon emissions from aircraft and the possibility of reaching the peak carbon emissions of the airport in the coming years by using scenario analysis and the Monte Carlo simulation method. The results show that the total carbon emissions of Harbin Taiping International Airport will be 458,800 tonnes in 2023 and up to 581,100 tonnes in 2035; under the scenarios of green development and technological innovation, the airport's carbon emissions can reach their peak by 2035, which will be lower and reached earlier under the scenario of technological innovation; the airport can improve energy use efficiency, increase the utilization of renewable energy sources, establish a carbon emission monitoring system, and actively participate in the market for carbon emission monitoring systems. Airports can systematically build a development path for airport carbon peaking by improving energy efficiency, increasing the utilization rate of renewable energy, establishing a carbon emission monitoring system, actively participating in carbon trading in the market, etc., so as to reduce carbon emissions from airports and promote the transformation and upgrading of civil aviation into a green and low-carbon sector.

Keywords: carbon peak; carbon emission forecasting; carbon emission measurement; airport management

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1. Introduction

In September 2020, China proposed the dual-carbon goal regarding its carbon dioxide emissions, striving to achieve peak emissions by 2030 and carbon neutrality by 2060. Focusing on the dual-carbon goal, various industries and fields in China have adopted a series of carbon reduction measures and are striving to promote the low-carbon transformation and upgrading of the industry. In order to actively respond to the "dual-carbon" goal, the Civil Aviation Administration of China (CAAC) issued a series of policy documents to guide the industry's green and low-carbon development; determine the theme of promoting the

high-quality development of civil aviation; become a pioneer in achieving carbon peak and carbon neutrality; and promote the overall policy of green, low-carbon, and recycling development of civil aviation [1]. The CAAC encourages large civil aviation enterprises to play a leading role in industry demonstration, scientific preparation, and the implementation of green development planning and carbon peak and carbon neutrality action plan, and put forward a phased target ensuring that "by 2035, airport carbon dioxide emissions gradually enter the peak platform period" [2].

With the rapid development of the national economy and the general improvement in people's living standards, the demand for air travel has become increasingly strong. The data released by the International Air Transport Association (IATA) show that the passenger throughput of China's civil aviation increased from 486 million to 1.352 billion in the decade of 2009–2019, which is an increase of 178% [3]. With the continuous growth of passenger throughput, the carbon emissions generated in the civil aviation sector are also gradually rising. Against the background of the dual-carbon goal, how to promote low-carbon transformation and upgrading in civil aviation, followed by high-quality development, is a key issue that needs to be solved in this field. Therefore, considering the rapid development of China's civil aviation industry, it is necessary to carry out research on the measurement of airport carbon emissions and the prediction of peak carbon emissions, in order to provide a theoretical basis for accelerating the realization of peak carbon emissions as well as the transformation and upgrading of civil aviation toward achieving low carbonization.

In recent years, the issue of carbon emission reduction in civil aviation has received more and more attention from scholars, and some scholars have carried out relevant research on the measurement and prediction of airport carbon emissions. Carbon emissions in airports mainly come from terminals, ramp areas, and aircraft. The carbon emissions of the first two are mainly measured by the authoritative factor emission method. As for the measurement of airport aircraft carbon emissions, there are two mainstream research methods, namely "top-down" and "bottom-up". Yilmaz adopted a "top-down" approach and calculated the carbon emissions during the LTO phases of an airport aircraft and analyzed the effects of time changes on carbon emissions during the LTO phases [4]. However, the "top-down" method has some disadvantages; for instance, fuel data are difficult to obtain, and the accuracy is not high compared with the "bottom-up" method based on operational data. Currently, among the "top-down" carbon emission measurement methods, the carbon emission measurement method for aircraft recommended by the International Civil Aviation Organization (ICAO) is the most authoritative. In terms of carbon emission prediction, scenario analysis is the most widely used comprehensive prediction method. Zhou et al. predicted the carbon emissions of China's civil aviation from the perspectives of fuel type and fuel intensity by using scenario analysis [5]. Liu et al. predicted the future carbon emissions of China's civil aviation by using scenario analysis, taking into account multiple factors such as transportation intensity and carbon emission coefficients [6]. The scenario analysis method in the current study involves setting a fixed rate of change for each influential factor, which is somewhat subjective. In fact, the rate of change in different variables in the future is uncertain, and the potential rate of change in each variable should be a continuous value rather than a specific value. Monte Carlo simulation, as a trend forecasting method, is widely used in uncertainty scenario analysis studies, but it cannot reveal the differences between scenarios due to different carbon reduction trends. If scenario analysis and Monte Carlo simulation can be organically combined, the complementary advantages of quantitative and qualitative methods will help to scientifically predict the evolutionary trends of carbon emissions and carbon peaking under different scenarios.

Therefore, in this study, we adopted the ICAO method based on operational data to measure the carbon emissions from aircraft and the factor emission method to measure the carbon emissions from airport terminals and ramp areas and combined the scenario analysis method with Monte Carlo simulation to predict the carbon emission trends of airports in the future years.

2. Methodology

2.1. Methodology for Measuring Carbon Emissions from Airports

Carbon emissions from the airport terminal and ramp areas were calculated using the emission factor method with the following Formula (1):

$$E_t = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} C_i \cdot I_i \quad (1)$$

where E_t is the total carbon emissions of the airport terminal and ramp areas (kg); E_i is the carbon emissions generated by the *i*th type of energy consumed by the airport terminal and the ramp area (kg); C_i is the energy use of the *i*th type of energy (kg); and I_i is the carbon emission factor of the ith type of energy ($kg \cdot kg^{-1}$). The main energy emission factor is determined in accordance with the national standard "Calculation Standard for Carbon Emissions from Buildings".

For the measurement of carbon emissions of aircraft, we adopted the "bottom-up" method based on operational data established by the ICAO, which calibrated the length of aircraft operation in each phase, namely takeoff 0.7 min, climb 2.2 min, approach 4 min, and taxiing 26 min, and the specific calculation formulas (Equations (2) and (3)) are as follows:

$$F_i = \sum_{i} T_{i,j} \cdot R_{i,j} \cdot N_i \quad (2)$$

$$E_a = \sum_{i} F_i \cdot I \cdot n_i \quad (3)$$

where i is the type of aircraft; j is the 4 different phases of aircraft LTO, i.e., takeoff, climb, approach, and taxi; F_i is the fuel consumption (kg) of an aircraft of category i in one LTO; $R_{i,j}$ is the fuel consumption rate (kg/s) of one engine in phase j; N_i is the number of engines of an aircraft of category i; and $T_{i,j}$ is the operation time (s) of an aircraft of category i in phase j. E_a is the carbon emission (kg) of the aircraft in the LTO stage; I is the fuel carbon emission factor (kg/kg); and n_i is the total number of LTOs of the aircraft of category i (times).

Combining the carbon emissions from the airport terminal and ramp areas as well as aircraft, the total carbon emissions of the airport, E, are obtained using Equation (4):

$$E = E_t + E_a \quad (4)$$

2.2. Settings for Carbon Emission Scenarios

Based on the evolutionary trend of past carbon emissions and different influencing factors of Harbin Taiping Airport, the effectiveness of existing policy implementation, and the potential space for emission reduction, we constructed the following four carbon emission scenarios:

(1) Scenario 1: Initial scenario: This is a possible scenario based on the characteristics and trends of civil aviation development in the past. The scenario assumes that civil aviation development is in a state of inertia: there are no changes in the current economic environment and at the technological level, no new emission reduction measures are taken, and the characteristics of civil aviation development will remain the same as in the past. Specifically, the rate of aircraft modernization will remain at the current level, with less use of biofuels and more use of conventional fuels.

(2) Scenario 2: Optimization scenario: The 13th Five-Year Development Plan for Energy Conservation and Emission Reduction in Civil Aviation states that the civil aviation industry should make efficient use of energy resources, optimize the energy-efficient operating environment of aviation, and strive to improve transportation productivity. The optimization scenario assumes that the civil aviation industry has implemented some emission reduction measures based on the initial scenario: through the initial implementation of the optimization strategy, the energy efficiency of airport operation equipment is improved,

more energy-efficient devices are adopted, the taxiing time of aircraft on the ground begins to decrease, and the efficiency of ground operation is improved to a certain extent; airlines, with the support of the government subsidies, gradually phase out old aircraft with high fuel consumption and gradually increase the use of biofuels.

(3) Scenario 3: Green development scenario: The 14th Five-Year Plan for Green Development of Civil Aviation puts forward the concept of sustainable development of civil aviation, emphasizes the realization of an ecological civilization, and highlights saving resources and protecting the environment as a basic national policy. Therefore, China has been gradually moving toward green development. On the basis of the optimization scenario, the green development scenario further highlights implementing low-carbon and green modifications in airports; adopting more energy-saving measures; and achieving low-carbon emission reductions by reducing ground taxiing time, lowering the fuel consumption rate of aircraft, and increasing the proportion of biofuel used.

(4) Scenario 4: Technological innovation scenario. Technological innovation is a central driver of energy efficiency and emissions reductions, particularly in terms of improving energy efficiency and the use of low-carbon energy sources. Major breakthroughs in airport operations, production, and energy storage technologies are critical, including a reduction in the cost of biofuel research and development, significant improvements in fuel efficiency, and the development of new types of aircraft to utilize biofuel, resulting in significant reductions in fuel consumption rates.

2.3. Monte Carlo Simulation Method

Due to the uncertainty of carbon emissions in the LTO phases of an aircraft, a prediction using scenario analysis alone cannot simulate the impact of uncertainty, resulting in poor prediction accuracy. Therefore, we adopted the Monte Carlo simulation method to calculate the target variables based on a certain probability of randomly combining the reference variables. The Monte Carlo method takes into account the uncertainty of the variables in the simulation prediction and provides a relatively scientific and reasonable assessment of the changes in future trends. The probability distribution of different evolutionary paths of carbon emissions was calculated using this method, and the most probable evolutionary path was obtained. According to the potential rate of change and the probability of the occurrence of the parameters C_i, $T_{i,j}$, $R_{i,j}$, I, and n_i under the above four scenarios, Monte Carlo simulation can be used to obtain the random values of different factors: $T_{i,j}$ conforms to the normal distribution, with a variance of 0.02; C_i, $R_{i,j}$, I, and n_i conform to normal distribution, with a variance of 0.01. Firstly, according to the relevant parameter settings, the probability distribution function under different scenarios was obtained by regression, considering that the airport was the only location for which the probability distribution of carbon emission was obtained. Using the probability distribution function and taking into account the uncertainty of airport operation, random sampling was carried out 20,000 times; then, a probability model was established for simulation, and finally, the prediction results were plotted and analyzed using Python v3.11.5 and Origin 2024 (10.1).

3. Data Sources and Research Hypotheses

Harbin Taiping International Airport was selected as a case study for this research. This airport is one of the 10 international aviation hubs in China and the only international aviation hub in Northeast China. Harbin Taiping International Airport is a large airport with domestic and international scheduled flights, and along with the other three major airports in Northeast China, serves as a backup airport for flights to North America and polar destinations; at the same time, Harbin Taiping International Airport is an important hub for connecting the northeast region and the city of Harbin to global destinations, and it is planned to be developed into an international aviation hub, reaching Northeast Asia and connecting to the U.S. and Europe in the near and long term, as well as a modern comprehensive transportation hub for Northeast China and a new power source for regional economic development in the Longjiang River in 2023. In 2023, the airport will have a

passenger throughput of 20.805 million, ranking among the top airports in China and guaranteeing 147,900 aircraft movements. The data used in this paper and their sources are shown in Table 1.

Table 1. Airport-related parameters and data sources.

Parameter	Data Sources
Total airport electricity consumption	Airport Operations Statistics
Fuel consumption of airport vehicles	Airport Operation Statistics
Aircraft movements	Civil Aviation Administration of China (CAAC) official website's National Civil Transportation Airport Production Statistics Bulletin.
Flight aircraft type data	National Flight Schedules for Summer/Autumn and Winter/Spring Seasons by the CAAC and airlines over the years
Engine matching parameters	Official website of the ICAO
Flight taxiing time	Previous research [7] and Civil Aviation Transportation Control Center reports.
Carbon emission factor of aviation fuel	Referring to the previous research results [6,8,9], 3.115 $kg \cdot kg^{-1}$ is taken.
Aircraft replacement rate	Previous research [10]
Aviation biofuel substitution rate	Previous research [5]
Carbon emission factor of airport energy use	Standard for building carbon emission calculation (GB/T 51366-2019)

The simulated probability distribution intervals of each parameter at the initial point using the Monto Carlo method (2023) and the target year for the four different forecast scenarios are shown in Table 2.

(1) Total airport power consumption: The total electricity consumption of the airport varied under the different forecasting scenarios. With the development of technology and the implementation of the dual-carbon policy, the energy consumption of the airport will be gradually reduced. Based on the trend of the airport's past electricity consumption statistics, it was assumed that the total electricity consumption of the airport would be reduced by −10%, 5%, 7%, and 10% under the four forecast scenarios, respectively.

(2) Taxiing time: The scheduling of aircraft at the airport varied under the different scenarios. Based on the standard taxiing time of 26 min given by the ICAO and the average taxiing time of 16 min for large airports around the world in 2017, it was assumed that the taxiing time would be reduced by 7.2%, 10.5%, 11.75%, and 20% for the four scenarios, respectively.

(3) Aviation fuel consumption rate: The new generation of aircraft engines can improve jet fuel efficiency by about 20% compared with the previous generation. It was assumed that 21%, 22.7%, 25%, and 25.9% of aircraft under the four scenarios would undergo engine upgrades or replacements and that the engine upgrades under the four scenarios would improve efficiency by 20%, 22%, 24%, and 27%, respectively. Additionally, we assumed that the percentage of improvement in jet fuel flow is the product of the engine upgraded or replaced parameter and the improved efficiency of the engine. Therefore, the fleet-wide jet fuel efficiency would increase by 4.2%, 5%, 6%, and 7% for the four scenarios, respectively.

(4) Aviation fuel carbon emission factor: There were some differences in the level of fuel improvement and input processes in the different scenarios, and there were also some differences in the proportion of similar alternatives to fuel, namely biofuel and new energy fuels. Therefore, it was assumed that the carbon emission factors of the different scenarios would be reduced by 0%, 0.5%, 0.6%, and 1.1%, respectively.

(5) Number of landings and takeoffs: Based on the number of aircraft movements at Harbin Taiping International Airport from 2010 to 2021, the regression method was used, and the number of aircraft movements at Harbin Taiping International Airport was predicted to be 177,354, 212,825, and 225,389 in 2025, 2030, and 2035, respectively.

Table 2. Parameter settings for different forecasting scenarios.

Scenario Type	Parameter Settings		Year				Probability Interval
			2023	2025	2030	2035	
Initial Scenario	Airport power consumption/10,000 kW·h		5951.6	6055.8	6661.4	7327.6	[−1%, 1%]
	Taxiing time/min		36.75	34.18	32.18	30.30	[−2%, 2%]
	Fuel consumption rate/kg·s^{-1}	Takeoff	1.13	1.08	1.05	1.01	[−1%, 1%]
		Climbing	0.93	0.88	0.86	0.83	[−1%, 1%]
		Taxiing	0.31	0.29	0.28	0.27	[−1%, 1%]
		Approach	0.10	0.10	0.09	0.09	[−1%, 1%]
	Fuel carbon emission factor/kg·kg^{-1}		3.115	3.115	3.115	3.115	[−1%, 1%]
Optimization Scenario	Airport power consumption/10,000 kW·h		5505.3	5230.0	4968.5	4720.1	[−1%, 1%]
	Taxiing time/min		36.75	32.36	29.10	26.17	[−2%, 2%]
	Fuel consumption rate/kg·s^{-1}	Takeoff	1.13	1.07	1.01	0.96	[−1%, 1%]
		Climbing	0.93	0.87	0.83	0.79	[−1%, 1%]
		Taxiing	0.31	0.29	0.28	0.26	[−1%, 1%]
		Approach	0.10	0.10	0.09	0.09	[−1%, 1%]
	Fuel carbon emission factor/kg·kg^{-1}		3.12	3.02	2.95	2.88	[−1%, 1%]
Green Development Scenario	Airport power consumption/10,000 kW·h		5505.3	5119.9	4761.5	4428.2	[−1%, 1%]
	Taxiing time/min		36.75	31.86	28.29	25.12	[−2%, 2%]
	Fuel consumption rate/kg·s^{-1}	Takeoff	1.13	1.05	0.99	0.93	[−1%, 1%]
		Climbing	0.93	0.86	0.81	0.76	[−1%, 1%]
		Taxiing	0.31	0.29	0.27	0.25	[−1%, 1%]
		Approach	0.10	0.10	0.09	0.09	[−1%, 1%]
	Fuel carbon emission factor/kg·kg^{-1}		3.12	3.01	2.92	2.83	[−1%, 1%]
Technology Innovation Scenario	Airport power consumption/10,000 kW·h		5505.3	4954.7	4459.3	4013.4	[−1%, 1%]
	Taxiing time/min		36.75	29.68	24.20	19.73	[−2%, 2%]
	Fuel consumption rate/kg·s^{-1}	Takeoff	1.13	1.06	0.99	0.92	[−1%, 1%]
		Climbing	0.92	0.87	0.81	0.75	[−1%, 1%]
		Taxiing	0.31	0.29	0.27	0.25	[−1%, 1%]
		Approach	0.10	0.10	0.09	0.09	[−1%, 1%]
	Fuel carbon emission factor/kg·kg^{-1}		3.12	3.00	2.83	2.68	[−1%, 1%]

4. Results and Discussion

4.1. Measurement of Carbon Emissions from the Airport

According to the latest operation data of Harbin Taiping International Airport and the summer–autumn and winter–spring seasons of the Civil Aviation Administration of China and airlines, it can be seen that the number of aircraft movements at the airport in 2023 will be 147,907, and according to Formulas (1)–(4), the total carbon emissions from Harbin Taiping International Airport in 2023 is 458,800 tons.

4.2. Airport Carbon Peak Forecast

Based on the probability distribution function of the above parameters and Formulas (1)–(4), a Monte Carlo simulation model was built in Python, substituting the parameter values of the four different scenarios into the model, and taking 20,000 random samples to obtain the simulation results of carbon emissions and carbon peaks under the different scenarios, which are shown in Figures 1–4.

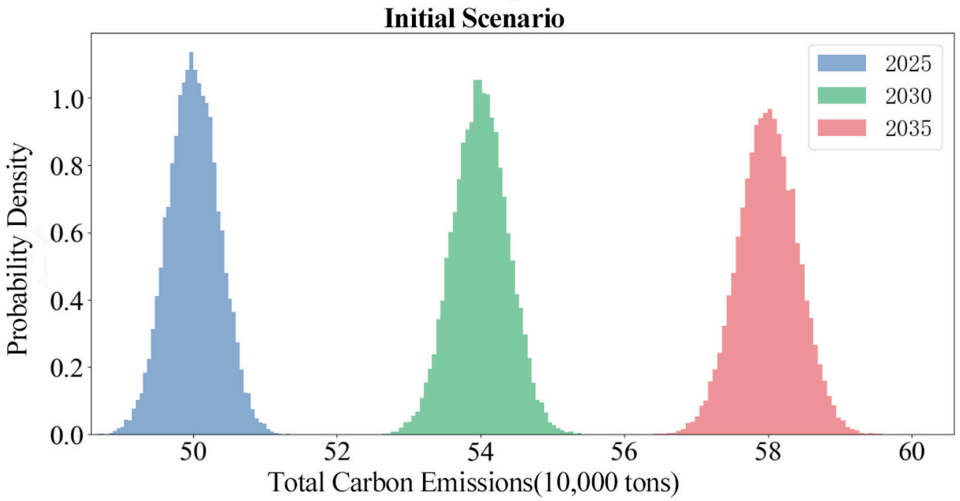


Figure 1. Carbon emission forecast in the initial scenario.

Figure 1 shows the results of carbon emission projections under the initial scenario. Under this scenario, the carbon emissions in 2025 will range from 489.1 to 512.8 million tons, with the most likely level of 502.1 million tons; in 2030, the carbon emissions will range from 527.9 to 553.8 million tons, with the most likely level of 540.9 million tons; and in 2035, the carbon emissions will range from 568.4 to 592.7 million tons, with the most likely level of 581.1 million tons. According to the calculation, there is no possibility of carbon peaking under the initial scenario. This result suggests that the airport's carbon emissions will continue to increase under the initial scenario, and according to the existing development pattern of the airport, carbon emissions will not be able to meet the national development goal of carbon peaking by 2030. Therefore, in order to curb the rising trend of carbon emissions, airports and airlines need to adopt more stringent measures to reduce emissions.

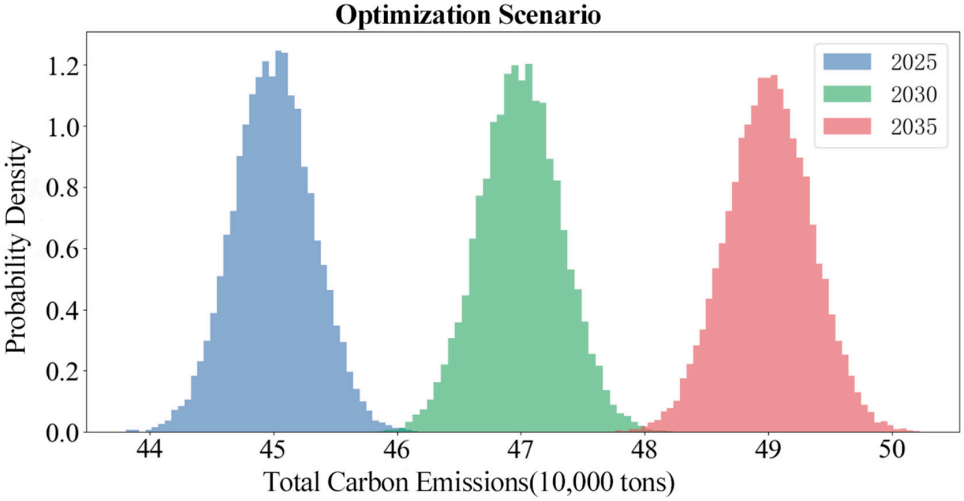


Figure 2. Carbon emission forecast in the optimization scenario.

Figure 2 shows the results of carbon emission projections under the optimization scenario. Under this scenario, the carbon emissions in 2025 will range from 438,300 to 460,800 tons, and the most likely level is 452,300 tons; the carbon emissions in 2030 will range from 459,900 to 480,300 tons, and the most likely level is 472,100 tons; the carbon emissions in 2035 will range from 478,100 to 502,700 tons, and the most likely level is 490,500 tons. According to the calculation results, there is still no possibility of reaching the carbon peak under the optimized scenario, but the overall carbon emissions are reduced compared with the initial scenario.

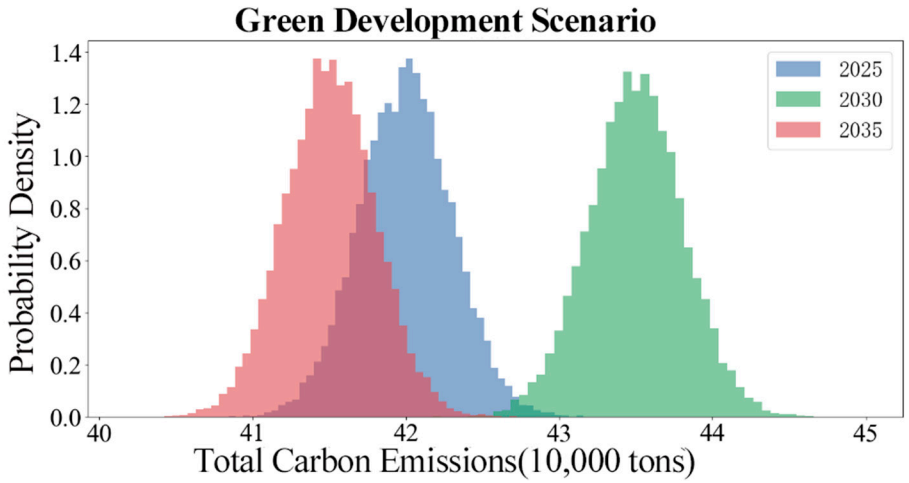


Figure 3. Carbon emission forecast in the green development scenario.

Figure 3 shows the results of carbon emission projections under the green development scenario. Under this scenario, carbon emissions in 2025 will range from 410,500 to 431,600 tons, with the most likely level of 423,100 tons; carbon emissions in 2030 will range from 426,800 to 445,900 tons, with the most likely level of 434,700 tons; carbon emissions in 2035 will range from 405,500 to 425,800 tons, with the most likely level of 414,200 tons. This indicates a reduction of 166,900 tons from the initial scenario, i.e., 166.9 million tons less than the initial scenario. It can be seen from the results in the figure that carbon peaking is realized under the green development scenario.

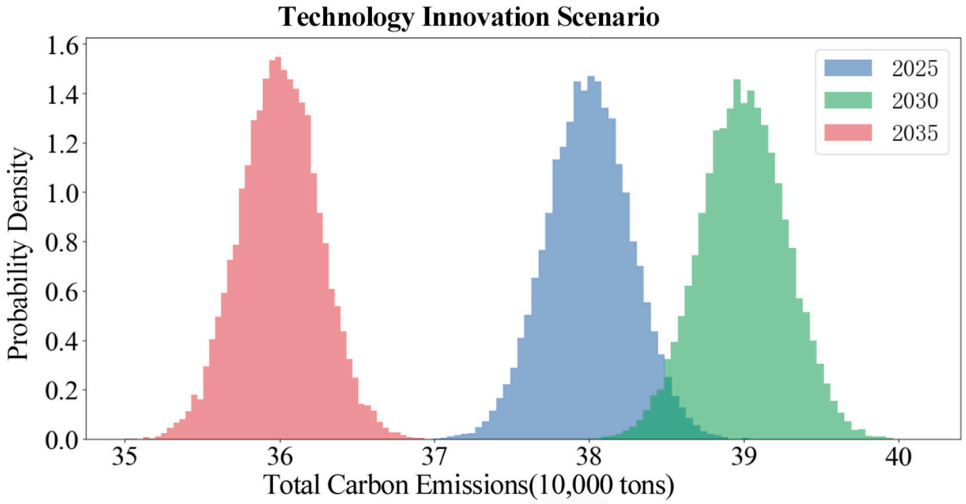


Figure 4. Carbon emission forecast in the technology innovation scenario.

Figure 4 shows the results of carbon emission projections under the technological innovation scenario. Under this scenario, the carbon emissions in 2025 will range from 368,200 to 390,200 tons, and the most likely level is 382,200 tons; the carbon emissions in 2030 will range from 380,700 to 399,700 tons, and the most likely level is 389,900 tons; the carbon emissions in 2035 will range from 350,900 to 369,500 tons, and the most likely level is 361,100 tons, which is 22,100 tons less than the initial scenario. According to the results, it can be seen that the carbon peak is realized in the technology innovation scenario, and it is the development scenario with the earliest carbon emission peak and the lowest future carbon emission among the four scenarios. Thus, airports should invest more in low-carbon technology in the future to promote the transformation and upgrading of the civil aviation sector to a low-carbon and green industry.

Based on the past operation data of the airport and the predicted results of the airport's carbon emissions under the four scenarios, a carbon emission evolution trend diagram of Harbin Taiping International Airport was constructed, as shown in Figure 5. It can be seen that under the initial and optimization scenarios, carbon peaking will not be achieved by 2035, while under the green development scenario and the technological innovation scenario, carbon peaking will be achieved; the shaded area in the figure shows the potential for airport's carbon emission reduction.

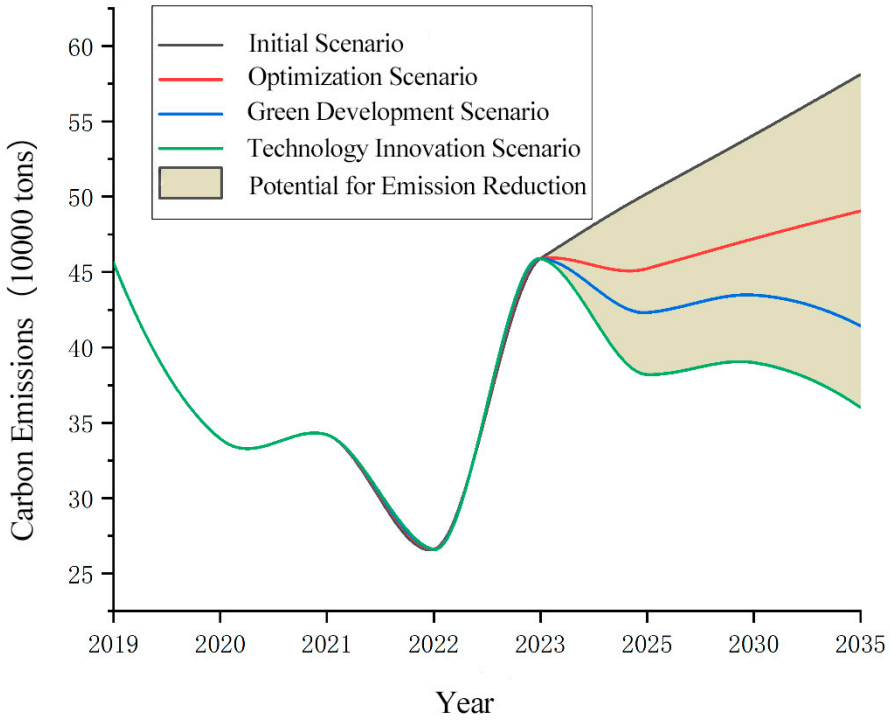


Figure 5. The evolutionary trend of carbon emissions of Harbin Taiping International Airport.

4.3. Airport Carbon Reduction Measures

According to the results of the airport carbon emission prediction, it can be seen that, according to the existing development and operation mode, it is impossible to reach the 2035 carbon peak development goal, in order to promote the green and low-carbon transformation and upgrading of civil aviation. Thus, corresponding emission reduction measures should be taken, which mainly include the following:

(1) For improving energy utilization efficiency, improving the lighting system and using high-efficiency lighting equipment such as LED lights, as well as adopting energy-saving air-conditioning systems and optimizing air-conditioning management, can prove beneficial. In addition, reducing energy loss by upgrading the thermal insulation of buildings can also significantly reduce carbon emissions.

(2) To actively utilize renewable energy, installing solar photovoltaic panels on the roofs of airport buildings and utilizing solar energy to generate electricity, as well as providing clean energy for the airport through wind power generation systems, are effective measures. Promoting airport buildings to pass green building certifications such as LEED (Leadership in Energy and Environmental Design) can also further reduce carbon emissions.

(3) In terms of aircraft emission reduction, airport management should focus on runway construction and planning. Specifically, the construction of parallel runways can significantly optimize the ground taxiing path of aircraft and reduce taxiing time. This not only helps to reduce fuel consumption and carbon dioxide emissions during aircraft ground operations but also improves overall operational efficiency, thus

providing dual benefits for environmental protection and operations. In addition, the optimization of taxiing routes and improvement in ground control systems are also measures worthy of consideration to further reduce energy consumption and the environmental impact of aircraft during ground operations.

(4) For ground operations, ground vehicles can be replaced with electric or hybrid models to reduce fuel consumption and emissions. Promoting the use of electric ferries and electric baggage trailers within airports can also effectively reduce carbon emissions. Adopting an intelligent dispatching system to improve the utilization rate of ground vehicles and equipment, reduce idling and idleness, optimize the ground operation process, and reduce unnecessary energy consumption are also important emission reduction measures.

(5) Establishing a carbon emission monitoring system to monitor the carbon emissions of each segment of the airport in real time, issuing carbon emission reports on a regular basis, displaying the results of emission reduction in an open and transparent manner, evaluating the effects of emission reduction measures on a regular basis, continuously optimizing and improving the emission reduction strategies according to the actual situation, and cooperating with scientific research institutions to explore new emission reduction technologies and methods are also important means of ensuring the effective implementation of emission reduction measures.

(6) Actively participating in carbon trading in the market is another important strategy. Taking into account the relevant policies of the state and the industry, as well as the construction process of the national carbon trading market, market opportunities should be fully identified to actively participate in carbon trading in the market such as carbon quota and forest carbon sinks. Carbon asset investment in renewable energy projects and forestry carbon sink projects should be carried out in a timely manner to accumulate high-quality carbon assets, continuously improve the ability to comply with carbon emission regulations, and prepare for the eventual realization of the dual-carbon target.

5. Conclusions

With the vigorous development of civil aviation, the consequent increase in carbon emissions cannot be ignored, and how to rapidly promote the low-carbon and green transformation of civil aviation to meet the dual-carbon goal is an urgent problem that needs to be solved. In this study, we took Harbin Taiping International Airport as the case study object and selected the three main sources of carbon emission in airports, namely the terminal building, the ramp area, and the aircraft, as the research scope. We used the ICAO method and the emission factor method to measure the airport's carbon emissions, and based on the scenario analysis method and the Monte Carlo simulation, we predicted the carbon emissions of the airport under four different scenarios of future development, providing the corresponding emission reduction measures and carbon peak development suggestions of the airport. The total carbon emission of Harbin Taiping International Airport in 2023 was estimated to be 458,800 t. In 2035, the predicted carbon emission of the airport under the green development scenario was estimated as 414,200 t, which was 166,900 t less than that of the initial scenario, a decrease of 28.7%, with a huge potential for emission reduction. Thus, in the future, the civil aviation sector should pay attention to the problems related to the current carbon emission rates in airports and actively take corresponding emission reduction measures, specifically focusing on the following aspects: improving energy efficiency, actively utilizing renewable energy sources, focusing on runway construction and planning, adopting an intelligent dispatch system, improving the utilization rate of ground vehicles and equipment, establishing a carbon emission monitoring system, and actively participating in the market carbon trading; then, a carbon-peak development plan can be established so as to promote the green development of the civil aviation sector.

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