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Evaluation of Carbon Emission Efficiency and Optimization of Optimal Emission Reduction Path in Hainan Tourism Based on Data Envelopment Calculation Analysis

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ABSTRACT
As a large tourism province, Hainan Province produces carbon emissions from the tourism industry that should not be underestimated. In view of the problems reflected, this paper designs a research program based on the data envelopment analysis model to evaluate the carbon emission efficiency of Hainan's tourism industry and optimize the emission reduction path. The tourism industry of 10 regions in Hainan Province is taken as the object of this study, and the DEA-SMB model is designed. Drawing on existing research results, nine carbon emission efficiency evaluation indicators for the tourism industry in Hainan are set, in addition to improving the principle of measuring carbon emissions and energy consumption in the tourism industry. In order to better promote the green, low-carbon and sustainable development of the tourism industry, it is proposed to adopt the DEA-SMB model to optimize the carbon emissions of the tourism industry in Hainan Province. Finally, the 2005-2024 Hainan Tourism Statistical Yearbook is taken as the main data source of this study, and combined with related research data, the optimization effect of carbon emission efficiency and emission reduction path of Hainan tourism industry is explored. In the optimization process of tourism carbon emissions in 10 regions of Hainan Province, the model of this paper has a particularly prominent effect on the optimization of tourism emission reduction in region C, and its emission reduction efficiency is increased to 64.21%, which verifies the tourism emission reduction effect of the model of this paper, and also reflects that there is still a huge room for improvement in local tourism emission reduction projects in Hainan Province.

Keywords: DEA-SMB model, Hainan tourism industry, carbon emission efficiency, emission reduction path optimization

1. Introduction

In recent years, global climate change has become increasingly severe, and carbon emissions have become a global concern [1]. Tourism is closely related to climate change, tourism is the second most affected industry by climate change after agriculture, while carbon emissions from transportation, accommodation and other tourism activities also affect climate change [2-4]. Nowadays, reducing

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anthropogenic carbon emissions and realizing low-carbon development has become a commonly accepted development concept [5]. Low-carbon tourism is the positive response of the tourism industry to climate change, but also an extension of the low-carbon economy, which will bring far-reaching impacts to the global tourism industry, but there are still many problems to be solved in order to truly realize the low-carbon development of the tourism industry [6-9].

Hainan is a tropical island tourist destination in China, with unique natural resources and unique marine culture, and is one of the fastest growing tourism regions in China [10-11]. At the same time, tourism is also an important pillar industry in Hainan Province. In the face of global climate change and carbon emission pressure, the tourism industry in Hainan Province is in urgent need of exploring the path of carbon peaking and carbon neutrality [12-14]. In order to realize the sustainable development of tourism, Hainan Province needs to actively explore the strategies of carbon peak and carbon neutrality to reduce the negative impact of tourism on carbon emissions [15-16]. In the process of achieving carbon peak, carbon emissions can be reduced by controlling the sources of carbon emissions, starting from transportation, hotels and attractions [17]. In addition, the goal of carbon neutrality can be achieved through the development of renewable energy sources and the adoption of carbon sequestration measures. These efforts will effectively reduce the negative impacts of tourism on the environment and lay a solid foundation for the sustainable development of tourism in Hainan Province [18-21].

After clarifying the theme and content of this research, the DEA-SMB model and the carbon emission of tourism in Hainan Province are taken as the accounting model and research object respectively. With the support of theoretical knowledge from relevant References, nine indicators are selected to form the evaluation index system of carbon emission efficiency of Hainan tourism, and also added that the research data come from the Tourism Statistical Yearbook of Hainan Province from 2005 to 2024. On the basis of carbon emission and energy consumption measurement in tourism, it is proposed to use the DEA-SMB model to optimize the tourism emission reduction project in Hainan, and finally complete the overall structure of the research work in this paper. In summary, using the model of this paper, to explore the carbon emission efficiency of Hainan tourism industry and the optimal emission reduction path optimization results.

2. Research on the optimization of carbon emission efficiency and emission reduction in Hainan's tourism industry

2.1. Accounting model and study population

2.1.1. Accounting models. The DEA model uses the idea of optimization and ideality, and its basic idea is as follows: first of all, the weight coefficients of the input and output indexes of each research object, i.e., decision-making unit (DMU), are taken as the optimization variables, and the input and output data of each DMU are compared, analyzed and optimized, and with the help of the data statistics and the mathematical planning method with the goal of the smallest inputs and the largest outputs, the construction of the "production frontier surface" (the optimal and most ideal state, i.e., the most efficient situation among all DMUs) [22]. Second, determine whether the DEA is effective by determining whether each DMU falls on the production frontier surface, and the DMUs falling on the production frontier surface are DEA effective [23]. Finally, for the DMUs with ineffective DEA, under the condition of keeping inputs and outputs unchanged, they are projected onto the production frontier, and their relative effectiveness is evaluated by comparing the degree of deviation from the production frontier, and the smaller the degree of deviation is, the higher the efficiency is, and at the same time, the projection line also points out the adjustment direction and the amount of adjustment for the improvement of the efficiency of DMUs [24]. The principle of calculation is as follows:

Suppose that in an evaluation system, there are n same type of $DMU_j\left(j=1,2,\cdots,n\right)$, whose input and output matrices in the process of economic production activities are $X_{ij}(x_{1j},x_{2j},\cdots,x_{mj})^T$,

$Y_{rj}(y_{1j}, y_{2j}, \cdots, y_{qj})^T$, where x_{ij} is the amount of inputs from the j th DMU to the i th factor, y_{rj} is the amount of outputs from the j th DMU to the r th factor, and x_{ij}, y_{rj} are both positive. Let the weight coefficients of the input and output matrices be $U_i = (u_1, u_2, \cdots, u_m)$ and $V_r = (v_1, v_2, \cdots, v_q)$. As a result, the efficiency evaluation value h_j of the j th DMU can be calculated by the following equation:

$$h_j = \frac{V_r^T \cdot Y_{rj}}{U_i^T \cdot X_{ij}} = \frac{\sum_{r=1}^{q} v_r \cdot y_{rj}}{\sum_{i=1}^{m} u_i \cdot x_{ij}} \tag{1}$$

DEA models have been widely used in efficiency evaluation studies since they were proposed, and they have unrivaled advantages over parametric methods. The traditional DEA models, including the two most basic DEA models, the CCR model with constant returns to scale (CRS) and the BCC model with variable returns to scale (VRS). Among them, the pairwise planning form of the input-oriented CCR model is shown below:

$$\theta^* = \min_{\lambda,\theta} \theta \tag{2}$$

$$s.t.\begin{cases} \sum_{j=1}^{n} x_{ij} \cdot \lambda_j \le \theta x_{io} \\ \sum_{j=1}^{n} y_{rj} \cdot \lambda_j \ge y_{io} \\ \lambda_j \ge 0 \\ j = 1, 2, \cdots, n \\ i = 1, 2, \cdots, m \\ r = 1, 2, \cdots, q \end{cases} \tag{3}$$

The model is an efficiency measure in which input indicators are scaled down in equal proportions according to θ, given the output. Where $\theta^* \left(0 \le \theta^* \le 1\right)$ represents the optimal solution of the model and is the efficiency value of the evaluated DMU_o. The λ_j represents the linear combination coefficients of DMU_j. Others are the same as in the previous section. When $\theta^* = 1$ for the evaluated DMU_o, it means that the evaluated DMU_o is DEA efficient, and the production frontier thus constructed is scale reward invariant. The above is the input-oriented CCR model, and the output-oriented CCR model, on the other hand, uses θ as the adjustment coefficient of the output indicator for model construction. The BCC model, compared with the CCR model, only in the constraints more than $\sum_{j=1}^{n} \lambda_j = 1$ constraints, its validity judgment is similar to the CCR model, the difference is that there are more judgments on the return to scale of the evaluated DMU_o situation.

The traditional DEA model has been improved by a large number of scholars, and synthesizing the advantages of the above improved models, this paper selects the super-efficient SBM model containing non-expected outputs [25-26]. Under the conditions of global, non-radial, non-angle, and constant returns to scale, the carbon emission efficiency of Hainan tourism is evaluated, and the specific expression of the model is:

$$\theta^* = \min_{\lambda, s^-, s^+} \frac{1 + \frac{1}{m} \sum_{i=1}^{m} \frac{s_i^-}{x_{io}^t}}{1 - \frac{1}{q+h} \left(\sum_{r=1}^{q} \frac{s_r^+}{y_{ro}^t} + \sum_{k=1}^{h} \frac{s_k^-}{b_{ko}^t} \right)} \tag{4}$$

$$s.t.\begin{cases} x_{io}^t \geq \sum_{t=1}^{T}\sum_{j=1,j\neq o}^{n} \lambda_j^t x_{ij}^t - s_i^-, i=1,2,\cdots,m \\ y_{ro}^t \leq \sum_{t=1}^{T}\sum_{j=1,j\neq o}^{n} \lambda_j^t y_{rj}^t + s_r^+, r=1,2,\cdots,q \\ b_{ko}^t \geq \sum_{t=1}^{T}\sum_{j=1,j\neq o}^{n} \lambda_j^t b_{kj}^t - s_k^-, k=1,2,\cdots,h \\ \lambda_j^t \geq 0(\forall j), s_i^- \geq 0(\forall i), s_r^+ \geq 0(\forall r), s_k^- \geq 0(\forall k) \end{cases} \tag{5}$$

where $\theta^*\left(0\leq\theta^*\right)$ is the efficiency value. t represents the year. x_{io} represents the i th input of the o th DMU. y_{ro} represents the r th desired output of the o th DMU. b_{ko} represents the k th non-expected output of the o th DMU. s_i^- represents the slack variable for inputs, i.e., the amount of input excess. s_r^+ represents the slack variable for desired outputs, i.e., the amount by which desired outputs need to be increased. s_k^- represents the slack variable for undesired outputs, i.e., the amount by which undesired outputs need to be curtailed.

2.1.2. Objects of study. In this paper, a total of 10 counties and cities in four regions of Hainan Province are used as the decision-making unit (DMU) for the study, which are divided into four major regions according to the regional division method promulgated by the National Bureau of Statistics in 2011: the eastern region (County B: Anding County, County C: Tunchang County), the northeastern region (County D: Lingao County, County E: Chengmai County), the central region (County F: Qiongzhong County, County G: Baisa County, and County H: Lingshui County), and the western region (County I: Changjiang County, County J: Baoting County, County K: Ledong County), spanning the period 2005-2024, totaling 20 years.

2.2. Indicator selection and data sources

2.2.1. Selection of indicators. Generally speaking, the more the number of indicators, the more it can reflect the real efficiency value, but a large number of studies have shown that the ratio between the number of indicators (X) and the number of decision-making units (DMUs) using the DEA-SBM model needs to be controlled in the ratio of X ⩽ 1/3 DMUs, and the number of indicators in this paper totaled 9, and the number of DMUs totaled 30, which is in line with the principle of the number of indicators in the DEA model. Secondly, according to the connotation of the DEA model, it is necessary to categorize the resource, environmental and economic indicators of the tourism industry's carbon emission efficiency, and this paper divides the above three types of indicators into desired output indicators, non-desired output indicators and input indicators, and the evaluation index system of Hainan's tourism industry's carbon emission efficiency is shown in Table 1. Economic indicators are “good output” categorized as desired output indicators, while the environmental impact of tourism carbon emissions is the largest “bad output” categorized as non-desired output indicators, resource consumption indicators are input indicators. In addition, in order to exclude the influence of price fluctuations, the total tourism revenue in this paper adopts the consumer price index of past years deflated to the constant price of 2005, and the tourism fixed asset input adopts the fixed asset investment price index of past years deflated to the constant price of 2005.

Table 1. Tourism carbon emission efficiency evaluation index system

Index division	Indicator category	Specific composition of indicators	Symbol
Expected output	Economic output	Gross tourism income	A1
	Tourism attraction	Total number of tourists	A2
Resource input	Labor input	Tourism practitioners	A3

	Capital investment	Investment in tourism fixed assets	A4
	Significant resource input	Number of star-rated hotels	A5
		Number of A-level tourist attractions by region	A6
		Number of travel agencies	A7
	Energy consumption	Total tourism energy consumption	A8
Undesirable output	Environmental impact	Total carbon emissions from tourism	A9

2.2.2. Data sources. In this paper, carbon emissions from tourism are selected as an indicator of environmental pollution, i.e. non-desired output. Carbon emission is the most important aspect of the tourism industry's impact on the environment, which comes from the consumption of energy, and in order to measure the carbon emission of the tourism industry, it is necessary to identify the relevant sectors of the tourism industry first. However, the tourism industry involves "food, accommodation, transportation, tourism, shopping, entertainment", and its characteristics determine that the carbon emissions of the tourism industry have multiple pathways and directly or indirectly generate carbon emissions, so it is almost impossible to accurately calculate the carbon emissions and energy consumption in the tourism industry, and it can only be estimated through the tourism-related sectors. According to the results of the previous literature, it is found that the carbon emissions of tourism mainly come from tourism transportation, tourism accommodation and tourism activities, so this paper will also estimate the carbon emissions of Hainan's tourism industry from 2015 to 2024 from these three aspects.

2.3. Measurement of carbon emissions and energy consumption in the tourism industry

Tourism is a very comprehensive industry, involving food, housing, transportation, travel, shopping, entertainment and many other aspects, the characteristics of the industry determines that the tourism industry carbon emissions and energy consumption pathway is also diversified, and tourism-related links need to use energy and directly or indirectly generate carbon emissions, and the current lack of direct statistics on carbon emissions and energy consumption in the tourism industry can only be estimated by estimating, in order to improve the accuracy of the should be clearly identified The main areas of carbon emission and energy consumption in the tourism industry. Since carbon emissions and energy consumption in the tourism industry are measured from tourism transportation, tourism accommodation and tourism activities, this paper will also account for the carbon emissions and energy consumption of the tourism industry in the above three sectors through the "top-down" method.

2.3.1. Tourism Transportation Carbon Emissions and Energy Consumption. The product of the passenger turnover of the four modes of transportation and the corresponding tourism carbon emission and tourism energy consumption factors is used to estimate the carbon emission and energy consumption of tourism transportation, and its accounting model is:

$$C^{(\tau)}_{j\,\substack{\text{Carbon emissions}\\\text{from tourism transportation}}} = \sum_i \alpha_i F_{i\,\text{Carbon emissions}} C_{ij} \tag{6}$$

$$E^{(\tau)}_{j\,\substack{\text{Tourism Transportation}\\\text{Energy Consumption}}} = \sum_i \alpha_i F_{i\,\text{Energy consumption}} C_{ij} \tag{7}$$

Where i denotes railroad, highway, air and other four modes of transportation, α_i for the i class of passenger transportation modes of passenger traffic in the proportion of tourists, according to Wei Yanxu et al. measured the proportion of the national train tourists travel 31.6%, car 13.8%, aircraft 64.7%, other 10.6%, $F_{i\,\text{Carbon emissions}}$ is the carbon emissions per unit kilometer of the i th category of passenger transportation modes, and the carbon emissions per unit of the various tourism transportation modes are $133gCO_2/pkm$ for cars, $137gCO_2/pkm$ for airplanes, $27gCO_2/pkm$ for trains, and $66gCO_2/pkm$ for others. $F_{i\text{ Energy consumption}}$ is the energy consumption per unit kilometer of the i th passenger transport mode, and C_{ij} is the passenger turnover of the i th passenger transport mode in the j th region.

2.3.2. Carbon Emissions and Energy Consumption of Tourist Accommodation. Accommodation industry can be divided into various types according to its nature, such as business conference, leisure and vacation, theme hotels, etc. This study also adopts the carbon emission and energy consumption of star-rated hotels instead of the total carbon emission and energy consumption of tourism and accommodation industry. The accounting formula is:

$$C^{(H)}_{j\text{ Carbon emissions from tourist accommodation}} = n\beta_{\text{Carbon emissions}} N_j \tau_j \tag{8}$$

$$E^{(H)}_{\substack{j\text{ Energy consumption}\\ \text{of tourist accommodation}}} = n\gamma_{\text{Energy consumption}} N_j \tau_j \tag{9}$$

Where N_j, τ_j are the number of beds and room occupancy rate in j area, respectively, from Hainan Tourism Statistics Yearbook (2005-2024). $\beta_{\text{Carbon emissions}}$ and $\gamma_{\text{Energy consumption}}$ are constants, indicating the unit carbon emissions and unit energy consumption value per bed per night, respectively, but this conversion factor usually varies in different countries and regions, and some of the global countries/regions hotel unit energy consumption value, it can be seen that the conversion coefficient value varies greatly, Gössling in the study of global energy consumption in the hotel industry, take the average unit energy consumption value of 130MJ/bed night, combined with the domestic existing research, this paper take $\beta_{\text{Carbon emissions}} = 2.458g/$ bed/night [36, 71. 104-106], $\gamma_{\text{Energy consumption}} = 155MJ/$ bed/night, and n is a constant, taking $n = 365$ nights.

2.3.3. Carbon Emissions and Energy Consumption of Tourism Activities. Tourists are the main body of tourism activities, so the energy consumption of tourism activities mainly comes from the energy consumption generated by tourists in the process of playing. The formula for accounting carbon emission and energy consumption of tourism activities is:

According to the above analysis, it is not difficult to calculate the carbon emission and energy consumption of tourism accommodation by applying formulas (10) and (11), which are calculated as:

$$C^{(A)}_{\substack{j\text{ Carbon emissions}\\ \text{from tourism activities}}} = \sum_k \sum_m \beta_{k\text{ Carbon emissions}} P^m_{jk} \tag{10}$$

$$E^{(A)}_{\substack{j\text{ Energy energy consumption}\\ \text{for tourism activities}}} = \sum_k \sum_m \gamma_{k\text{ Energy consumption}} P^m_{jk} \tag{11}$$

and Compendium of Statistical Information on New China. $\beta_{k\text{ Carbon emissions}}$ and $\gamma_{k\text{ Energy consumption}}$ represent the average carbon emissions and average energy consumption generated by a tourist's participation in a k type of tourism activity, and p^m_{jk} is the tourists who participate in the k type of tourism activity among the j type tourists in the j region.

2.3.4. Carbon emissions and energy consumption in the tourism industry. Tourism Carbon Emissions and Energy Consumption for Tourism Transportation, Accommodation and Activities for the years 2015-2024, while the formula for calculating the total tourism carbon emissions and tourism energy consumption for the years 2015-2024 is as follows:

$$C_{\substack{\text{Carbon emissions}\\ \text{from tourism}}} = C^{(T)}_{\substack{\text{Carbon emissions from}\\ \text{tourism transportation}}} + C^{(H)}_{\substack{\text{Tourism Accommodation}\\ \text{Carbon Emissions}}} + C^{(A)}_{\substack{\text{Carbon Emissions}\\ \text{from Tourism Activities}}} \tag{12}$$

$$E_{\substack{\text{Energy consumption}\\ \text{in tourism}}} = E^{(T)}_{\substack{\text{Tourism transportation}\\ \text{energy consumption}}} + E^{(H)}_{\substack{\text{Tourism accommodation}\\ \text{energy consumption}}} + E^{(A)}_{\substack{\text{Energy consumption}\\ \text{of tourism activities}}} \tag{13}$$

The fastest average annual growth rate of energy consumption in tourism activities should be emphasized, while the average annual growth level of energy consumption in tourism accommodations has even been negative, indicating that the country's strong advocacy of the concept of green hotels on energy saving and emission reduction of tourism accommodations has achieved a better effect, and at the same time with the reduction in the number of star-rated hotels in some provinces across the country.

2.4. Optimization of emission reduction pathways in tourism

This subsection optimizes the abatement paths for the backward regions of China's tourism industry in terms of carbon emission reduction, which is divided into four parts: the first part is the data description, the second part calculates the efficiency of the tourism industry CO2 emissions in the backward regions based on the SBM model that considers the undesired outputs, the third part calculates the marginal abatement cost of the tourism industry CO2 emissions in the backward regions based on the SBM model that considers the undesired outputs, and the fourth part optimizes the abatement paths under the efficiency-cost constraint to optimize the emission reduction path.

2.4.1. Data description. In this paper, the amount of investment in tourism fixed assets, the number of employees in tourism and the energy consumption of tourism are used as input indicators, the total income of tourism represents the desired output, and the CO2 emission of tourism represents the non-desired output, and the investment in fixed assets and the total income of tourism are transformed into the constant price of 2005, so that the value of CO2 emission efficiency of the tourism industry of Hainan in the period of 2005-2024 can be calculated. In addition, this subsection also needs the number of employees in the tourism industry, the investment in fixed assets in the tourism industry and the total income of the tourism industry, all three of which are derived from the Hainan Tourism Statistical Yearbook and the Hainan Statistical Yearbook of the corresponding years.

2.4.2. Carbon emission efficiency after emission reductions. In this paper, the SBM model that takes variable slack and undesired outputs into account in the DEA methodology is used to measure the efficiency of CO2 emissions in tourism. Hypothesis:

$$\min \rho = \frac{1-(1/L)\sum_{q=1}^{L} s_q^- / x_{q0}}{1+\frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1} s_r^g / y_{r0}^g + \sum_{r=1}^{S_2} s_r^b / y_{r0}^b\right)}$$
$$s.t.\begin{cases} x_{q0} = X\delta + s_q^- \\ y_{r0}^g = Y^g\delta - s^g \\ y_{r0}^b = Y^b\delta + s^b \\ s_q^- \geq 0, s^g \geq 0, s^b \geq 0, \delta \geq 0 \end{cases} \tag{14}$$

Where: ρ denotes the CO2 emission efficiency value of the tourism industry in the range $[0,1]$. s_q^-, s^b and s^g denote the redundancy of inputs, non-desired outputs, and shortfalls in desired outputs, respectively. x_{q0}, y_{r0}^g and y_{r0}^b denote input, desired output and non-desired output variables, respectively, and δ is a weight variable. The larger the ρ, the higher the validity.

2.4.3. Marginal abatement cost of carbon after emission reductions. For ease of solution, Eq. (14) is transformed into the form of a linear program by means of the Charnes-Cooper transformation:

$$\omega = \min t - (1/L)\sum_{q=1}^{L} s_q^- / x_{q0}$$

$$s.t.\begin{cases} 1 = t + \dfrac{1}{S_1 + S_2}\left(\sum_{r=1}^{S_1} s_r^g / y_{r0}^g + \sum_{r=1}^{S_2} s_r^b / y_{r0}^b\right) \\ x_{q0}t = X\Lambda + S_q^- \\ y_{r0}^g t = Y^g\Lambda - S^g \\ y_{r0}^b t = Y^b\Lambda + S^b \\ S_q^- \geq 0, S^g \geq 0, S \geq 0 \\ \Lambda \geq 0, t \geq 0 \end{cases} \tag{15}$$

where $t > 0$ means that the change is reversible, and if the optimal solution of Eq. (15) is $(t^*, \Lambda^*, S_q^{-*}, S^{g*}, S^{b*})$, then the solution of this linear programming prototype is: $\left(t^*, \Lambda^*, S_q^{-*}, S^{g*}, S^{b*}\right)$, $\rho = \omega^*$, $\delta^* = \Lambda^* / t^*$, $s_q^{-*} = S_q^{-*} / t^*$, $s^{g*} = S^{g*} / t^*$, $s^{b*} = S^{b*} / t^*$. Based on the pairwise variation, the pairwise problem of Eq. (15) can be derived as:

$$\xi^* = \max \xi$$

$$s.t.\begin{cases} \xi + vx_{q0} - u^g y_{r0}^g + u^b y_{r0}^b = 1 \\ u^g Y^g - vX - u^b Y^b \leq 0 \\ v \geq (1/L)(1/x_{q0}) \\ u^g \geq (\xi / S_1 + S_2)(1/y_{r0}^g) \\ u^b \geq (\xi / S_1 + S_2)(1/y_{r0}^b) \end{cases} \tag{16}$$

An equivalent variation of Eq. (16) yields:

$$\max(u^g y_{r0}^g) - vx_{q0} - u^b y_{r0}^b$$

$$s.t.\begin{cases} u^g Y^g - vX - u^b Y^b \leq 0 \\ v \geq \dfrac{1}{L}(1/x_{q0}) \\ u^g \geq \dfrac{1 + u^g y_{r0}^g - vx_{q0} - u^b y_{r0}^b}{S_1 + S_2}(1/y_{r0}^g) \\ u^b \geq \dfrac{1 + u^g y_{r0}^g - vx_{q0} - u^b y_{r0}^b}{S_1 + S_2}(1/y_{r0}^b) \end{cases} \tag{17}$$

where $1/x_{q0}$ denotes the row vector. v denotes the dyadic price of inputs, u^g denotes the dyadic price of desired output, and u^b denotes the dyadic price of undesired output. If it is further assumed that the shadow price of desired output is equal to its market price (or normalized to 1), the shadow price p^b of the undesired output associated with it is:

$$p^b = p^y \cdot \frac{u^b}{u^y} \tag{18}$$

2.4.4. Optimization of emission reduction pathways after emission reduction. On the basis of the previous CO2 emission reduction efficiency and marginal abatement cost, their rank types are divided, and the rank types of CO2 emission efficiency and marginal abatement cost in the tourism industry are divided as shown in Table 2, and the two-dimensional matrix of CO2 emission efficiency and marginal abatement cost is shown in Fig. 1. Carbon dioxide emission efficiency and marginal abatement costs are regrouped into hierarchical types, i.e., the first and second levels of the original carbon dioxide emission efficiency level are combined into a high-efficiency type and the third level is a low-efficiency type, and the first and second levels of the original marginal abatement cost level are combined into a high-cost type and the third level is a low-cost type. And based on this type classification, a two-dimensional matrix diagram is drawn to analyze the optimization path of energy conservation and emission reduction in the backward region of carbon emission reduction in Hainan tourism.

Table 2. Rank type division

CO2 emission efficiency level	ρ -Value	Marginal abatement cost scale	ρ^b -Value(Yuan/ton)
Level 1	$0.7 \le \rho \le 1.0$	Level 1	$\rho^b \ge 30000$
Level 2	$0.4 \le \rho \le 0.7$	Level 2	$10000 < \rho^b < 30000$
Level 3	$0 \le \rho \le 0.4$	Level 3	$\rho^b < 10000$

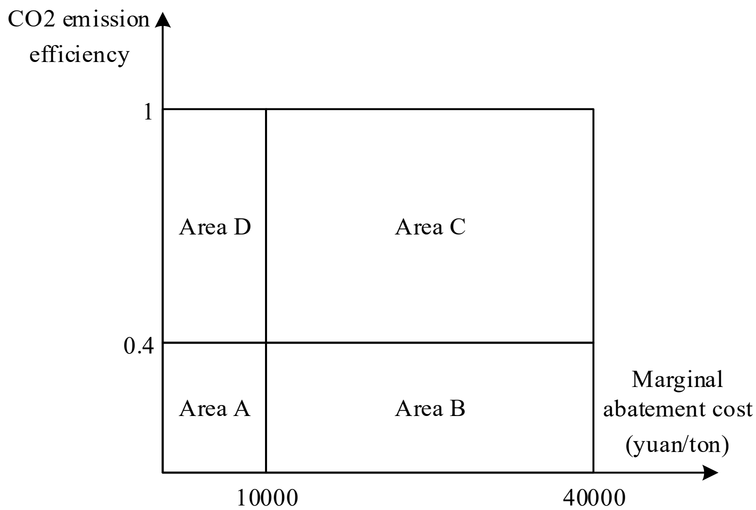


Fig. 1. Two-dimensional matrix

3. Carbon Emission Efficiency and Emission Reduction Optimization Assessment

3.1. Example Analysis of Carbon Emissions from Hainan's Tourism Industry

The first two parts of this chapter discuss the formation mechanism of tourism carbon emission efficiency, the measurement model and the selection and measurement of input and output indicators of the model, and finally construct the DEA-SBM-based carbon emission efficiency model of tourism in Hainan Province, and the study will use the model of this paper to measure the carbon emission efficiency of the tourism industry in the 10 regions (B~K) of Hainan Province, and carry out a detailed analysis of the results of the efficiency measurement in terms of both time and space. The study will measure the carbon emission efficiency of the tourism industry in 10 regions (B~K) of Hainan Province and analyze the results in detail from both time and space.

3.1.1. Time-varying characteristics of carbon efficiency in the tourism industry. The trend of the average value of the carbon emission efficiency of the tourism industry in the 10 regions of Hainan Province from 2005 to 2024 is shown in Fig. 2. In order to show the regional differentiation characteristics of the efficiency, the study is divided into the eastern, northeastern, central and western regions to carry out the comparative analysis of the efficiency according to the criteria for the division of the three major economic zones in China. As a whole, during the study period, the carbon emission efficiency of China's tourism industry has shown a fluctuating upward trend, with the average value of its efficiency increasing from 0.424 in 2005 to 0.636 in 2024, indicating that Hainan's tourism industry has been effective in transforming into a low-carbon, intensive industry, but there is still a potential for improvement of 35.77% away from the effective frontier. The main reason for this is the impact of the SARS epidemic in 2003, which depressed the tourism market and reduced the output capacity of the tourism economy, and reduced its efficiency value to a low level. From 2008 to 20011, the tourism market gradually recovered and the level of the tourism economy gradually improved, and the overall efficiency average changed in a “several” shape during this period. The year 2011 is one of the important turning points of the carbon emission efficiency of Hainan tourism industry, as the initial year of the Eleventh Five-Year Plan period, the carbon emission efficiency level of the tourism industry after 2011 has shown an upward trend year by year, and the average value of the overall efficiency reaches 0.406 in 2021, but there is still a certain distance from the effective frontier. 2021 is another important turning point in the change of the average value of carbon emission efficiency of the tourism industry during the study period. After 2021, the national efficiency growth rate is greatly improved, and the average value of efficiency is raised from 0.475 in 2021 to 0.636, which is stepping into the ranks of the middle level. The development of carbon emission efficiency in Hainan's tourism industry can be roughly divided into three periods: (1) The stage of deepening the marketization process of the tourism industry (2005-2011). The overall efficiency level in this period showed an oscillating decline. Affected by the epidemic, the tourism industry's economic resilience is insufficient, and the growth of the tourism economy in some areas mainly relies on factor-quantitative inputs, which triggers resource consumption and ecological damage, and is the main reason why the efficiency is at a low level. (2) The stage of “comprehensive integration of the tourism industry into the national strategy” (2012-2020). During this period, the average value of the overall efficiency shows a steady upward trend, with the deepening of the tourism industry and the rapid growth of national demand for travel, the economic contribution of the tourism industry has become more and more prominent, and the tourism industry has transformed from the development of key regions to the development of the tourism industry in the whole region of the country, and the transformation capacity of the tourism economy has been continuously strengthened, but the development of the tourism industry during this period also has a series of problems such as imbalance in the industry structure, shortage of tourism talents, high energy However, tourism development in this period also suffers from a series of problems such as imbalance in industrial structure, shortage of tourism talents, high energy input and high carbon emission, which have slowed down the speed of efficiency improvement to a certain extent. (3) High-quality development and transformation stage (2021-2024). During this period, tourism economic growth and the construction of ecological civilization have entered a benign development stage, and while tourism economic output is expanding, tourism environmental pollution can be controlled, and the carbon emission efficiency of the tourism industry has achieved remarkable results in terms of “improving quality and efficiency”. With the implementation of the “Two Mountains” theory and the green development concept, the tourism industry is constantly transforming to low-carbon and high-efficiency development.

In terms of regions, the eastern region is generally in the lead in terms of the average efficiency level during the study period, and the trend of its efficiency curve is basically similar to that of the northeastern region. Specifically, the carbon emission efficiency of the tourism industry in the eastern region changes to an upward trend after a fluctuating decline at the beginning of the study period, and after 2021, the efficiency curve of the eastern region is overtaken by the central region, ranking second. The main reason for this change is that the transportation network in the eastern region is becoming more and more complete, and tourism transportation occupies a higher proportion in the energy consumption structure, especially air travel, and the carbon emissions generated in recent years have largely constrained the improvement of the efficiency level in the region. Second, the early development of tourism in the eastern region and the diminishing marginal benefits of the tourism economy, which are reflected in declining growth rates of economic output and increasing or unchanged trends in the growth rates of undesired output, have made it difficult to realize efficiency changes.

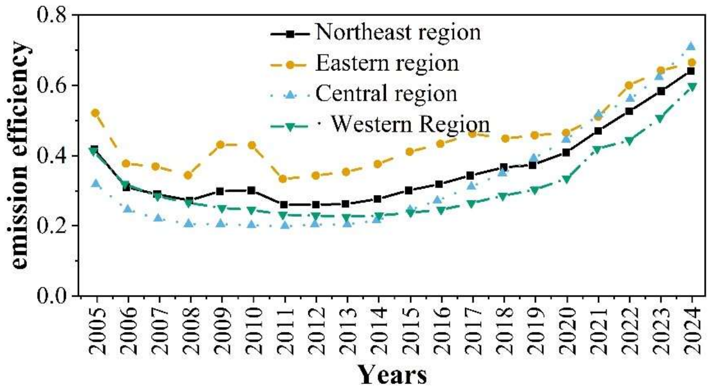
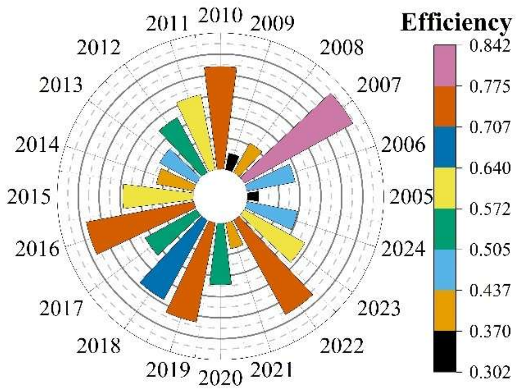
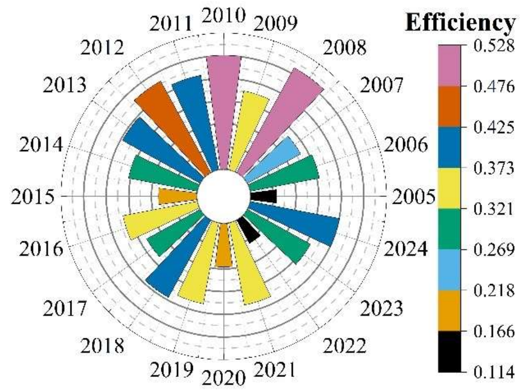


Fig. 2. Variation characteristics of mean carbon emission efficiency

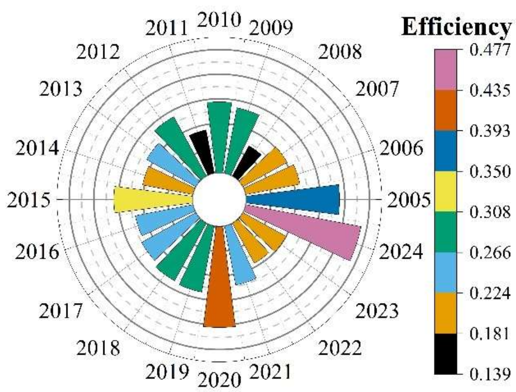
Figure 3 shows the time-series changes in the mean value of carbon emission efficiency of tourism in 10 regions of Hainan during the study period, where (a) to (j) are regions B to K, respectively. Region J (mean carbon emission value: 0.824), Region G (mean carbon emission value: 0.720), Region B (mean carbon emission value: 0.555), and Region F (mean carbon emission value: 0.516) are in the leading position in terms of the carbon emission efficiency level of the tourism industry, and in particular, the values of the carbon emission efficiency of the tourism industry in both Region J and Region G are greater than 0.7, indicating that the two regions are relatively close to the efficiency frontier unit in terms of reducing factor inputs, maintaining the tourism This indicates that these two regions are closer to the efficiency frontier unit in terms of reducing factor inputs, maintaining economic growth and minimizing carbon emissions, with relatively small potential for efficiency improvement. However, the carbon emission efficiency level of tourism in H (average carbon emission value: 0.378), K region (average carbon emission value: 0.354), C region (average carbon emission value: 0.329), area E (average carbon emission value: 0.329), region I (average carbon emission value: 0.275), and area D (average carbon emission value: 0.263) is generally lower than 0.5, and there is still a certain gap between the carbon emission efficiency level of tourism in other regions, indicating that there may be redundancy of factor input in these provinces and regions. Problems such as insufficient economic output or excessive carbon emissions lead to a high degree of efficiency loss. Overall, from the perspective of the trend of change, the carbon emission efficiency of the tourism industry in the 10 regions of Hainan at the end of the study is still at a medium level, and there is still a certain distance from the effective frontier, with more room for efficiency improvement.



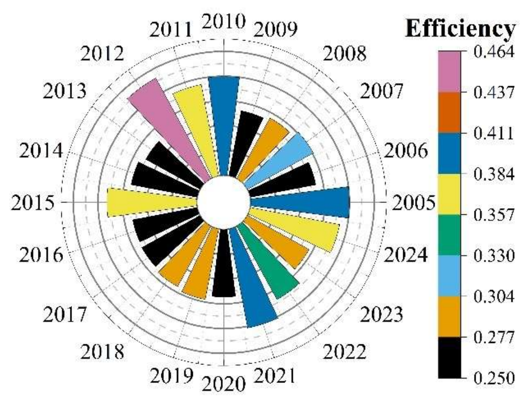
(a)B Region



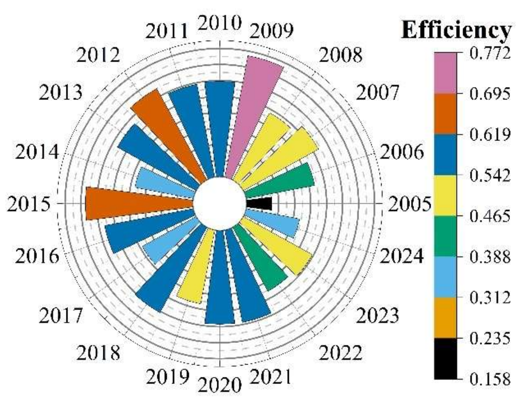
(b)C Region



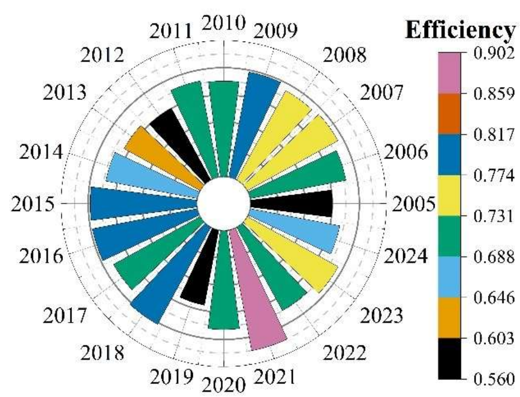
(c)D Region



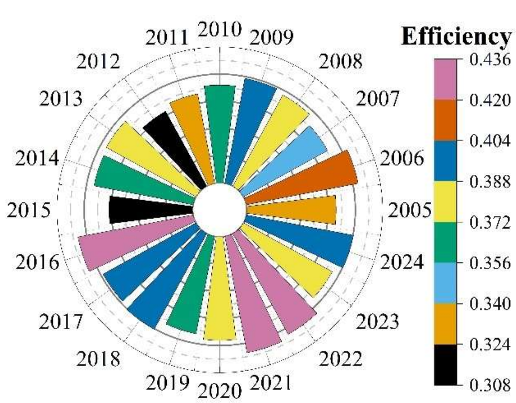
(d)E Region

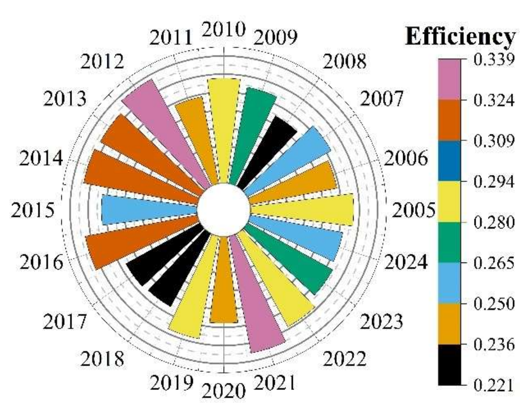


(e)F Region

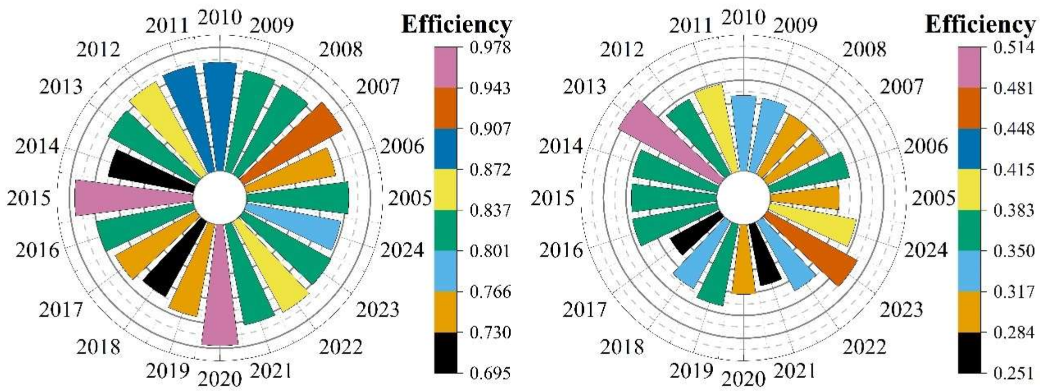


(f)G Region





(g)H Region (h)I Region



(i)J Region (j)K Region

Fig. 3. Average carbon emission efficiency of tourism in 10 regions

3.1.2. Characteristics of spatial variations in carbon emission efficiency in the tourism industry. The 10 areas in Hainan Province in the observation year are divided into four categories: high-intensity carbon emission areas, medium-high intensity carbon emission areas, medium-low intensity carbon emission areas and low-intensity carbon emission areas. efficiency average value of the tourism industry in Hainan Province, between 50% and 100%, between 100% and 150% of the average value of the tourism industry's carbon emission efficiency in Hainan Province, and higher than 150% of the average value of the tourism industry's carbon emission efficiency in Hainan Province in the high-intensity carbon emission zone. The spatial changes in the carbon emission efficiency of the tourism industry are characterized in Table 3, where M represents the average value of the carbon emission efficiency of the tourism industry. For example, in 2005, the low-intensity carbon emission zone (less than 0.210) did not exist, the medium-intensity carbon emission zone (0.210~0.420) had C (0.310), D (0.223), E (0.270), H (0.419), I (0.244), and K (0.358), and the medium-high-intensity carbon emission zone (0.420~0.630) had B (0.483), F (0.436), and high-intensity carbon emission area (greater than 0.60) has G (0.718), J (0.738), and the remaining 2006 to 2024 is based on the data in the table, and will not be expressed in detail. It confirms that the model of this paper can accurately detect the real situation of carbon emission efficiency of tourism industry in 10 regions of Hainan Province during the period of 2005~2024 and reasonably divide it, which can provide auxiliary decision-making for low-carbon management of relevant departments.

Table 3. Spatial variation characteristics of tourism carbon emission efficiency

Name	B	C	D	E	F	G	H	I	J	K	0.5M	1M	1.5M
2005	0.483	0.310	0.223	0.270	0.436	0.718	0.419	0.244	0.738	0.358	0.210	0.420	0.630
2006	0.842	0.269	0.204	0.304	0.536	0.761	0.354	0.264	0.915	0.294	0.237	0.474	0.712
2007	0.411	0.527	0.140	0.280	0.478	0.748	0.383	0.221	0.825	0.302	0.216	0.432	0.647
2008	0.330	0.353	0.270	0.267	0.772	0.786	0.393	0.270	0.833	0.328	0.230	0.460	0.690
2009	0.741	0.502	0.288	0.398	0.595	0.702	0.360	0.289	0.879	0.333	0.254	0.509	0.763
2010	0.614	0.423	0.178	0.375	0.590	0.720	0.335	0.244	0.873	0.393	0.237	0.475	0.712
2011	0.549	0.460	0.275	0.463	0.651	0.602	0.315	0.338	0.857	0.379	0.244	0.489	0.733
2012	0.453	0.392	0.227	0.251	0.563	0.639	0.377	0.315	0.816	0.514	0.227	0.455	0.682
2013	0.432	0.309	0.208	0.273	0.372	0.686	0.372	0.319	0.704	0.381	0.203	0.406	0.608
2014	0.588	0.169	0.319	0.364	0.673	0.787	0.308	0.263	0.958	0.378	0.240	0.481	0.721
2015	0.773	0.334	0.238	0.266	0.565	0.786	0.432	0.315	0.802	0.381	0.245	0.489	0.734
2016	0.531	0.269	0.251	0.269	0.385	0.728	0.391	0.234	0.750	0.252	0.203	0.406	0.609
2017	0.683	0.389	0.267	0.279	0.609	0.814	0.402	0.230	0.696	0.339	0.235	0.471	0.706
2018	0.732	0.362	0.273	0.290	0.469	0.561	0.365	0.288	0.761	0.367	0.223	0.447	0.670
2019	0.543	0.192	0.410	0.273	0.584	0.726	0.381	0.239	0.977	0.307	0.232	0.463	0.695
2020	0.375	0.368	0.244	0.407	0.587	0.901	0.436	0.328	0.830	0.276	0.238	0.475	0.713
2021	0.765	0.117	0.185	0.339	0.456	0.698	0.423	0.293	0.841	0.349	0.223	0.447	0.670
2022	0.581	0.318	0.200	0.285	0.492	0.763	0.373	0.269	0.811	0.455	0.227	0.455	0.682
2023	0.496	0.401	0.476	0.369	0.340	0.671	0.401	0.260	0.780	0.388	0.229	0.458	0.687
2024	0.304	0.115	0.379	0.399	0.158	0.601	0.329	0.285	0.827	0.304	0.185	0.370	0.555

3.2. Example Analysis of Hainan Tourism Emission Reduction Optimization

Through the above, it can be seen that the efficiency of tourism carbon emissions in the vast majority of the above areas in Hainan is not ideal, so it is adjusted and optimized accordingly. After five rounds of corresponding iterative processing, all the regional efficiency data have realized the DEA-SMB model effectively 5 rounds of iterative adjustment of each stage of the efficiency adjustment process as shown in Figure 4. Under the optimization of the DEA-SMB model, because the peak number of carbon emissions from the tourism industry in Hainan is relatively fixed, so compared to the initial program, the adjusted areas have a different range of adjustment, the final optimization results are shown in Table 4. From the optimization results of carbon emissions from tourism, it can be seen that there are nine regions need to reduce the marginal abatement cost of carbon, and the remaining one region is to increase the marginal abatement cost of carbon, of which the most obvious effect of carbon emission reduction in the C region of Hainan Province, after optimization, the abatement efficiency of 64.21%, which fully confirms the effectiveness of the application of the DEA-SMB model in the optimal abatement path optimization above.

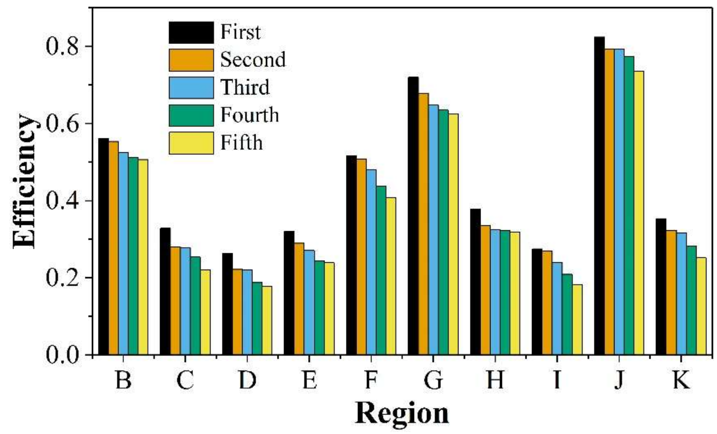


Fig. 4. Efficiency adjustment process

Table 4. Hainan tourism industry emission reduction optimization

Region	Marginal abatement cost scale		Adjust quantity	Emission reduction efficiency
	Initial value	Optimize value		
B	38145	27161	10984	28.80%
C	37271	13339	23932	64.21%
D	29827	23977	5850	19.61%
E	21296	10375	10921	51.28%
F	34234	22232	12002	35.06%
G	27168	12996	14172	52.16%
H	22101	14477	7624	34.50%
I	38092	13932	24160	63.43%
J	38631	26839	11792	30.52%
K	23476	27785	-4309	-18.35%

4. Conclusion

In this paper, the research object is firstly selected, DEA-SBM model is constructed, and the emission efficiency assessment indexes and data sources of Hainan tourism industry are determined with reference to previous research results. Subsequently, it gives the formula for measuring carbon emissions and energy consumption in tourism, and optimizes the tourism emission reduction path in Hainan Province with the help of the above model. Combined with the research data, the carbon emission efficiency of Hainan tourism and the optimization effect of emission reduction path are evaluated. After the optimization of the model in this paper, the emission reduction efficiency of the tourism industry in Area C of Hainan Province reaches 64.21%, which is especially obvious compared with the other nine areas, indicating that the DEA-SMB model can improve the carbon emission efficiency of the tourism industry in Hainan, so as to further improve the level of sustainable development of the local tourism industry in the region.

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