

Article

Analysis of the Driving Factors and Decoupling of Carbon Emissions from Energy Consumption in Hainan Province, China

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Abstract

High-energy-consuming and high-emission industries have made enormous contributions to economic development, but their carbon emissions are also substantial. To achieve the “dual carbon” goals as early as possible, this study takes Hainan Province, China, as the study area and employs the LMDI method to decompose the factors influencing carbon emissions. The Tapio model is also used to analyze the decoupling relationship between the driving factors and carbon emissions. The results show the following: (1) Carbon emissions in Hainan Province from 2007 to 2022 exhibited an overall upward trend, with an average annual growth rate of 5.75%. Various oil products accounted for an average share of over 40.11%, but the share of electricity increased, while that of oil decreased. The sectors, ordered from the highest to lowest carbon emissions, are: industry > transportation > residential > agriculture, forestry, animal husbandry, and fishery. (2) The decomposition results indicate that economic output, energy structure, and population size have positive effects on carbon emissions, while energy intensity and industrial structure have negative effects. At the sectoral level, the energy structure factor has a negative effect only on the transportation sector, and positive effects on all other sectors. The energy intensity factor has negative effects on all sectors except “other sectors” and the residential sector, with a cumulative contribution of 2003.65×10^4 tonnes of carbon emissions. The industrial structure factor has negative effects on carbon emissions across all sectors, with a cumulative contribution of 1568.23×10^4 tonnes. The economic output factor promotes emissions in all sectors, with a cumulative increase of 5787.35×10^4 tonnes, of which 2740.88×10^4 tonnes are from the industrial sector. The population factor also promotes emissions across all sectors, with a cumulative contribution of 549.21×10^4 tonnes. (3) The decoupling model analysis shows that from 2007 to 2008, the decoupling state was predominantly an unfavorable negative decoupling. From 2008 to 2010, it shifted to a favorable positive decoupling, but from 2010 to 2011 it returned to an unfavorable negative decoupling. From 2011 to 2022, the decoupling index declined from 1.43 to 0.13, indicating an overall favorable weak decoupling state. (4) The decoupling effects of individual influencing factors reveal that in the 2007–2008 period, the carbon emission decoupling index was mainly composed of the energy intensity effect and the economic output effect. In the

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2012–2013 period, the energy structure effect did not change significantly and remained in a weak decoupling state, while the energy intensity effect declined markedly, changing the decoupling state from weak to strong decoupling. The industrial structure effect remained in a strong decoupling state. In 2017–2018, the economic output effect changed from an expansive coupling state to a weak decoupling state, while the other effects all showed relatively favorable positive decoupling states. In 2021–2022, all effects exhibited favorable positive decoupling states, among which the energy structure and energy intensity effects showed strong decoupling. Finally, this study provides a case study for the development of Hainan as a Free Trade Port, a tourism island, a petroleum- and aviation-fuel-intensive province, and a pilot ecological civilization zone.

Keywords: Hainan Province; energy consumption carbon emissions; LMDI; Tapio decoupling; low-carbon development

1. Introduction

In recent years, global warming has continuously triggered extreme weather events such as heatwaves, floods, and rising sea levels. The methods of energy development and utilization profoundly affect the global climate, environmental quality, and ecological balance, making them a core issue in driving humanity toward sustainable development. Advancing the transformation of energy systems, achieving a sustainable energy supply, continuously improving living standards, and ensuring the enduring development of human society have become widely recognized global goals [1]. China has firmly maintained its position as the world's second-largest economy and is a major nation in terms of population and energy consumption; consequently, its efforts toward carbon reduction are crucial for global environmental governance. To demonstrate its responsibility as a major power, China has established key milestones: peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. To meet these “dual carbon” goals on schedule, it is essential to clarify the carbon emission trajectories of key regions and sectors. Notably, energy-related activities constitute the primary source of carbon emissions in China [2]. Hainan Province, a major Special Economic Zone and a National Pilot Zone for Ecological Civilization, plays a leading, exemplary role in the implementation of the “dual carbon” strategy. In 2022, Hainan's carbon emissions accounted for approximately 0.5% of the national total, with per capita emissions of 4.51 tonnes, placing it among provinces with low levels in both total emissions and emission intensity; however, against the backdrop of developing a Free Trade Port and a Special Economic Zone, sustained future economic growth could lead to a surge in carbon emissions. The *Outline of the 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives Through the Year 2035 of Hainan Province* mandates that Hainan rank among the top provinces nationwide in economic growth by 2025, achieving an average annual Gross Regional Product growth rate of over 10%. If this economic growth trajectory is maintained over the next decade, studies indicate that the growth rate of Hainan's energy consumption demand will exceed the national average by 36.4% [3]. Furthermore, compared to regions that are advanced in “dual carbon” implementation, Hainan still exhibits significant gaps in key indicators such as per capita GDP, the service sector's share of the economy, energy intensity, and total energy consumption. Faced with the coexistence of inherent low-carbon advantages and the imperative for rapid economic development, Hainan urgently needs to explore a path of coordinated development that balances economic growth with low-carbon constraints.

Regional carbon emissions are currently a hot topic in research. Existing research has examined carbon emissions at the regional scale, covering aspects such as emission estimation [4], spatiotemporal evolution trends [5], regional disparities [6], and driving factors [7]. First, regarding calculation methods, approaches include the material balance method [8], life cycle assessment [9], the emission factor method [10], modeling [11], and the physical decision tree method [12]. Second, common methods for analyzing influencing factors include the Tapio model [13], Granger causality test [14], geographically weighted regression [15], econometric models [16], the STIRPAT model [17], LMDI decomposition analysis [18], random forest regression [19], and social network analysis [20]. These influencing factors span economic [21], social [22], and environmental [23] dimensions, such as the level of economic development, urbanization, and energy intensity. Third, regional studies have been conducted at various scales, including provincial [24], prefecture-level city [25], and county levels [26], as well as across economic belts [27] and urban agglomerations [28]. Fourth, regarding data types, studies utilize energy consumption data [29] as well as coupled data combining energy consumption with nighttime light data [30]; nighttime light data enables high-precision carbon emission inversion at the grid scale, making it suitable for spatial analysis in contexts where direct monitoring of energy-related carbon emissions is lacking. Fifth, regarding the sectors studied, there is extensive research on individual sectors such as agriculture, forestry, animal husbandry, and fishery [31]; industry [32]; construction [33]; transportation [34]; wholesale and retail [35]; and the residential sector [36] but relatively few studies provide a comprehensive analysis across all sectors.

The Logarithmic Mean Divisia Index (LMDI) decomposition model is a decomposition method for measuring the influencing factors of carbon emissions. This model can decompose total carbon emissions, clarify the contribution of each factor, and accurately assess its impact on carbon emissions. The carbon emission decoupling effect refers to the decoupling relationship between economic growth and carbon emissions—that is, while the economy continues to grow, carbon emissions no longer increase in tandem, or even show a declining trend. The realization of this decoupling effect is an important indicator for measuring the sustainable development capacity of a country or region, a necessary pathway to achieving carbon peak and carbon neutrality goals, and also an important way to promote green and low-carbon economic transformation. Research on carbon emission decoupling broadly covers multiple key industries, especially those that contribute significantly to carbon emissions, such as transportation, energy, manufacturing, agriculture, construction, and tourism, and the decoupling effects and their driving factors have received extensive attention. The LMDI method is applied to comprehensively consider the influencing factors of carbon emissions in Hainan Province from energy, economic, and social perspectives. This study provides a case study for the development of Hainan as a Free Trade Port, a tourism island, a petroleum- and aviation-fuel-intensive province, and a pilot ecological civilization zone.

The innovations of our study are as follows: First, whereas some existing studies are confined to specific sectors, our research is not restricted by sectoral boundaries. Compared with single-industry studies, our work is more comprehensive and more conducive to formulating emission reduction policies at the sectoral level. Moreover, by systematically examining the temporal evolution path of carbon emissions over the long time series from 2007 to 2022, we help to fill the gap in current research, which mainly focuses on spatial differences. Second, compared with existing studies that frequently apply regional grid emission factors, our electricity-related carbon emissions are calculated based on Hainan Province's own grid carbon emission coefficients. Third, the basic structural decomposition models in existing studies do not consider the impact of different energy varieties and fuel types. In this study, we extend and decompose the original Kaya identity and

LMDI model to account for multiple sectors and energy consumption types related to carbon emissions. This helps to theoretically optimize the analytical framework of the LMDI model and improve the accuracy of empirical results. Finally, as China's largest Special Economic Zone and the only Free Trade Port, the significance of studying carbon emissions from energy consumption in Hainan extends far beyond a provincial case. It carries the strategic mission of exploring new pathways for green and high-quality development for the nation and even the world. This entails addressing the surge in energy demand after the full customs closure, transforming the advantages of clean energy into development drivers, and leading the promotion of new energy vehicles, among other challenges.

We utilized the IPCC Greenhouse Gas Emission Factor Database as the primary source for carbon emission factors. First, we compiled an inventory of carbon emissions from energy consumption across sectors, accounting for both fossil fuel consumption and regional electricity dispatch. Subsequently, by employing the LMDI model and the Tapio decoupling index, we analyzed the driving factors of carbon emissions and the decoupling status between economic growth and emissions in Hainan Province; we further investigated the contribution of factors such as energy structure, energy consumption intensity, industrial structure, economic output, and population size to the decoupling index. Consequently, Hainan Province's emission reduction strategies should prioritize lowering energy intensity, establishing a green energy system, and strengthening economic development to achieve high-quality growth. This study, which investigates the driving factors and decoupling effects of carbon emissions in Hainan Province, holds significant value for the region's pursuit of low-carbon development.

2. Research Methods and Data Sources

2.1. Data Sources

The economic and demographic data used in this study were obtained from the *Hainan Statistical Yearbook* [37]. Energy consumption data were sourced from the China Carbon Emission Accounts and Datasets (CEADs). Carbon emission coefficients were derived from the following sources: the National Greenhouse Gas Emission Coefficient Database (<https://data.ncsc.org.cn/factoryes/index>; accessed on 6 May 2026) and the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [38].

2.2. Research Methods

2.2.1. Carbon Emission Calculation Methods

Based on the carbon emission accounting methods outlined in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, this study estimated the carbon emissions of Hainan Province, China; the specific calculation method is as follows [39]:

$$C = \sum_{i=1}^{11} E_i \times K_i \quad (1)$$

In the formula, C represents the total carbon emissions; K_i denotes the carbon emission coefficient of the fuel i ; and E_i indicates the fuel i consumption (converted to standard coal equivalent). In the calculation process, carbon emissions are accounted for by the final energy consumption sectors, and the coefficients for energy conversion and carbon emissions are shown in Table 1 [40].

Table 1. Carbon emission calculation parameters for various energy types.

Energy Types	Standard Coefficient/(kgce/kg)	Carbon Emission Coefficient (kgC/kgcece)
Raw coal	0.7143	1.9003

Coke	0.9714	2.8604
Crude oil	2.4286	3.0202
Gasoline	1.4714	2.9251
Kerosene	1.4714	3.0179
Diesel	1.4571	3.0959
Fuel oil	1.4286	3.1705
LPG	1.7143	3.1013
Refinery gas	1.5714	3.0119
Natural gas	1.5714	2.1622
Electricity	1.2290	0.3648

2.2.2. Construction of a Decomposition Model for Carbon Emission Drivers

The Kaya identity was extended. The expanded Kaya identity is shown below [41]:

$$\begin{aligned}
 C &= \sum_{i=1}^n \sum_{j=1}^m C_{ij} \\
 &= \sum_{i=1}^n \sum_{j=1}^m \frac{C_{ij}}{E_{ij}} \frac{E_{ij}}{E_i} \frac{E_i}{G_i} \frac{G_i}{G} \frac{G}{P} P \\
 &= \sum_{i=1}^n \sum_{j=1}^m CE_{ij} \times CS_{ij} \times EG_i \times CG_i \times HPG \times P \\
 &= \Delta CE_{ij} +
 \end{aligned} \tag{2}$$

In this formula, i denotes the industry type; n is the total number of industry types; j denotes the energy type; m is the total number of energy types; C_{ij} is the carbon emission of the i energy type in the j industry; E_{ij} is the consumption of the i energy type in the j industry (converted to standard coal equivalent); G_i is the industrial economic output of the i industry; G is the per capita GDP; P is the population; CE_{ij} denotes the carbon emission coefficient of energy; CS_{ij} represents the energy consumption structure; EG_i is the energy consumption intensity of each industry; CG_i is the industrial structure; HPG is the per capita GDP; and P is the population.

Since the emission intensity of fossil fuels C_{ij} is assumed to be time-invariant, its differential effect in the LMDI model is zero, and we have therefore omitted this factor. Finally, five factors were selected to analyze their impact on carbon emission growth, namely, energy structure, energy intensity, industrial structure, per capita GDP, and population.

2.2.3. Construction of a Model for Decoupling Economic Growth from Carbon Emissions

Based on the Tapio decoupling theory, a decoupling index model for economic growth and carbon emissions in Hainan Province is constructed [42]:

$$E = \frac{\Delta C / C}{\Delta G / G} \tag{3}$$

where E is the decoupling elasticity index, $\Delta C / C$ is the rate of change in current-year carbon emissions relative to the base-year carbon emissions, and $\Delta G / G$ is the rate of change in current-year GDP relative to the base-year GDP.

To further analyze the impacts of energy structure, energy consumption intensity, industrial structure, economic output, and population size on the decoupling status, their contributions to the decoupling elasticity index are as follows:

$$E = \Delta C_{cs} \frac{G}{\Delta G \times C} + \Delta C_{eg} \frac{G}{\Delta G \times C} + \Delta C_{cg} \frac{G}{\Delta G \times C} + \Delta C_{hpg} \frac{G}{\Delta G \times C} + \Delta C_p \frac{G}{\Delta G \times C} \quad (4)$$

$$= E_{cs} + E_{eg} + E_{cg} + E_{hpg} + E_p$$

E_{cs} 、 E_{eg} 、 E_{cg} 、 E_{hpg} 、 E_p are the contributions of energy structure, energy consumption intensity, industrial structure, economic output, and population size to the decoupling elasticity index, respectively.

Based on Tapio theory and taking into account environmental pressure, economic growth, and the specific range of the decoupling index, the relationship between economic growth and carbon emissions in Hainan Province is categorized into three types and eight decoupling states (as shown in Figure 1).

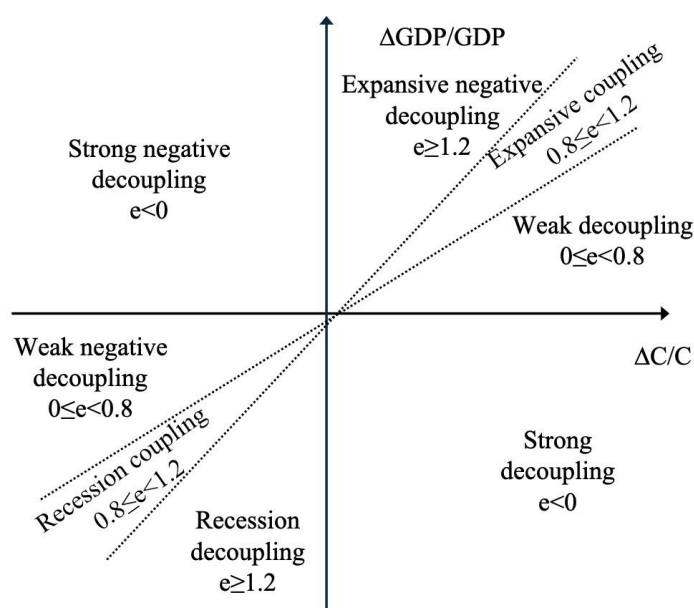


Figure 1. Decomposition of the decoupling model for economic growth and carbon emissions.

3. Empirical Results

3.1. Historical Carbon Emissions

As shown in Figure 2, carbon emissions in Hainan Province exhibited an overall upward trend from 2007 to 2022, with an average annual growth rate of 5.75%. The fastest growth occurred between 2007 and 2011, a period characterized by rapid economic expansion and an industrial structure dominated by the secondary sector (specifically industry and construction) alongside a heavy reliance on petroleum energy. Although the growth rate of carbon emissions slowed between 2012 and 2022, a significant spike of 9.84%, an increase of 425.14×10^4 tonnes, was recorded in 2021. The recovery of the tourism industry directly contributed to increased carbon emissions through associated activities such as transportation and accommodation [43]. Regarding the breakdown by energy type, the top three sources by share were petroleum products, electricity, and natural gas, in that order. Hainan's petroleum-dominated energy structure is primarily attributable to the transportation sector, where petroleum accounts for over 50% of carbon emissions. Kerosene is the largest contributor among petroleum products, a trend closely linked to the booming aviation industry; as an international tourism island, Hainan generates massive demand for transportation fuel across its tourism and logistics sectors. The share of electricity in the energy mix rose from 17.49% in 2007 to 33.97% in 2022, an increase of 16.48 percentage points. This rise is attributed to the high proportion of coal-fired power

capacity, which accounts for 67% of the total; despite Hainan's recent vigorous development of wind and solar power, with new energy sources now exceeding 50% of both installed capacity and power generation, coal-fired generation remains a significant component, resulting in a high share of carbon emissions from electricity [44]. The proportion of natural gas consumption peaked at 25.46% in 2013 and has declined annually since then. This decline was primarily driven by rising costs resulting from reduced gas supplies, prompting residential and industrial consumers to seek alternative energy sources, such as increasing their use of LPG, refinery dry gas, and electricity.

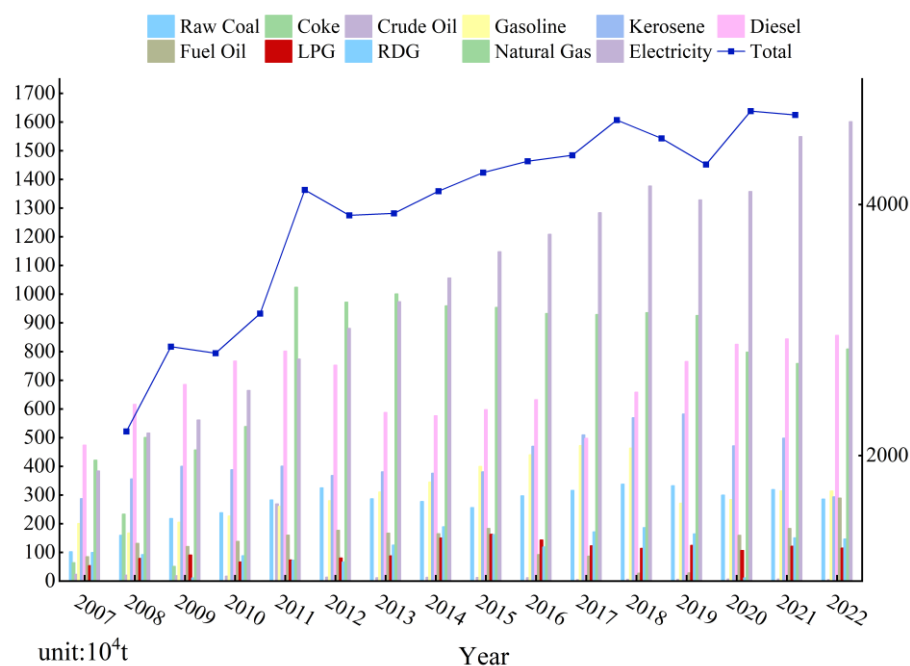


Figure 2. Historical carbon emissions by energy type.

3.2. Sectoral Carbon Emissions

As shown in Figure 3, the sectors, ranked by their share of carbon emissions from highest to lowest, are industry; transportation; the residential sector; and agriculture, forestry, animal husbandry, and fishery. The industrial sector accounts for the largest share of emissions among all sectors, with an average of 47.64% between 2007 and 2022; industry is a pillar of Hainan Province's economic development. Industrial activity entails continuous energy consumption, and certain foundational industries (such as cement and chemicals) are characterized by high energy consumption and high pollution, resulting in significant carbon emissions. Between 2007 and 2022, the industrial sector's share of carbon emissions fell from 54.47% to 47.79%, a decrease of 6.68 percentage points. This decline can be attributed to several factors: the introduction of the Implementation Plan for Carbon Peaking in Hainan's Industrial Sector, which clarified the goals, pathways, and key tasks for low-carbon industrial development, and the energy transition, which increased the proportion of clean energy use. Enterprises have been supported in undertaking technological upgrades for energy conservation and carbon reduction through measures that control carbon at the source and reduce it during processes [45]. China's first carbon capture unit for natural flue gas has been put into operation, achieving a carbon capture efficiency of over 90%. The transportation sector follows, with its share of emissions dropping from 22.79% in 2007 to 18.27%, though it remains a significant contributor. Analysis reveals that the transportation structure has shifted: the share of road transport in freight turnover has gradually declined, while the share of water transport

has risen to over 90%, significantly lowering carbon emissions. Furthermore, the sector has moved toward low-carbon operations by increasing the proportion of new energy vehicles; clean energy vehicles now account for 100% of newly added or replaced urban buses and taxis (including ride-hailing vehicles) across the province. In 2022, Hainan promoted the adoption of 122,000 new energy vehicles, representing 58.2% of all newly registered vehicles, the highest market penetration rate in the country. Meanwhile, the residential sector's share of carbon emissions rose from 5.53% in 2007 to 13.79%. This increase is driven by the acceleration of urbanization and rising living standards, which have led to greater energy demand; consequently, energy consumption (such as for air conditioning and home appliances) and associated carbon emissions among urban residents have grown rapidly. On the other hand, as Hainan Province develops into an international tourism island, the booming tourism industry has placed additional pressure on carbon emissions from the residential sector. Tourism-related activities such as accommodation, dining, and entertainment are inherently part of "household consumption," collectively driving up overall emissions in the residential sphere. The shares of other sectors are as follows: agriculture, forestry, animal husbandry, and fishery (7.05%); other sectors (7.16%); wholesale and retail (4.09%); and construction (2.16%) [46].

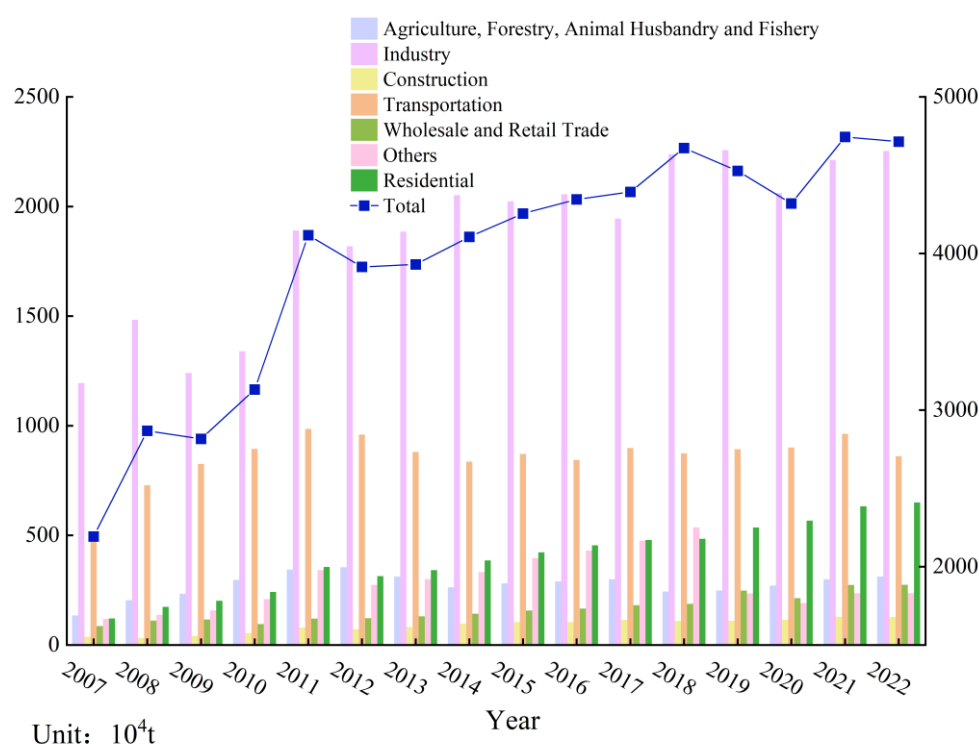


Figure 3. Carbon emissions from energy consumption by sector.

3.3. LMDI Decomposition Results of Influencing Factors

Based on time-series data for Hainan Province from 2007 to 2022, and utilizing the Kaya identity and the LMDI model, this study empirically analyzes the impacts of sectoral energy consumption structure, energy consumption intensity, industrial structure, economic development level, and population size on carbon emissions from energy consumption in Hainan Province. The annual effects of the influencing factors across different sectors during the study period are illustrated in Figures 4–8 and Tables 2–6 [47].

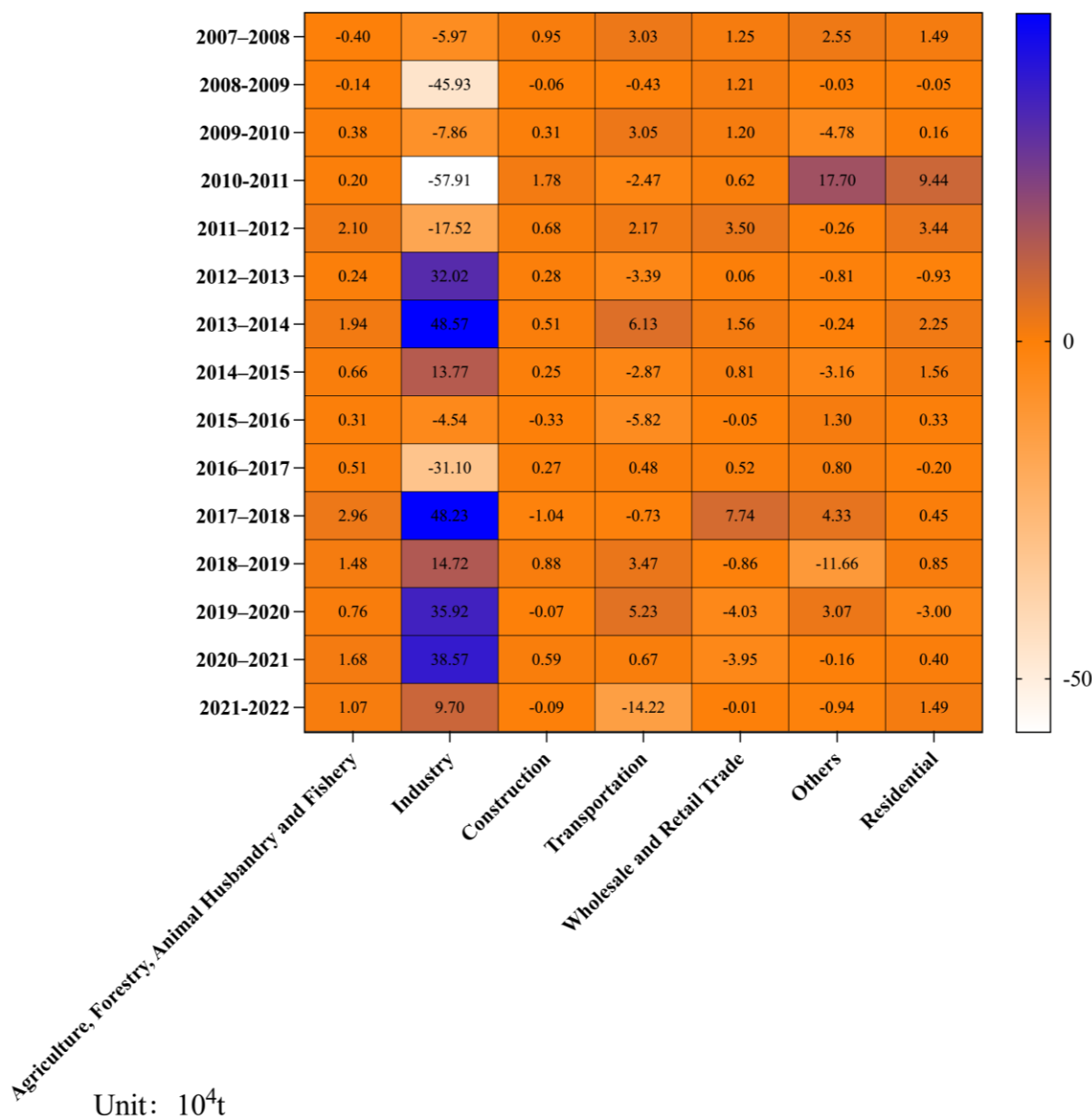


Figure 4. Energy structure effect.

Table 2. Energy structure effect.

Year	Agriculture, Forestry, Animal Husbandry and Fishery	Industry	Construction	Transportation	Wholesale and Retail Trade	Others	Residential
2007–2008	−0.40	−5.97	0.95	3.03	1.25	2.55	1.49
2008–2009	−0.14	−45.93	−0.06	−0.43	1.21	−0.03	−0.05
2009–2010	0.38	−7.86	0.31	3.05	1.20	−4.78	0.16
2010–2011	0.20	−57.91	1.78	−2.47	0.62	17.70	9.44
2011–2012	2.10	−17.52	0.68	2.17	3.50	−0.26	3.44
2012–2013	0.24	32.02	0.28	−3.39	0.06	−0.81	−0.93
2013–2014	1.94	48.57	0.51	6.13	1.56	−0.24	2.25
2014–2015	0.66	13.77	0.25	−2.87	0.81	−3.16	1.56
2015–2016	0.31	−4.54	−0.33	−5.82	−0.05	1.30	0.33

2016–2017	0.51	−31.10	0.27	0.48	0.52	0.80	−0.20
2017–2018	2.96	48.23	−1.04	−0.73	7.74	4.33	0.45
2018–2019	1.48	14.72	0.88	3.47	−0.86	−11.66	0.85
2019–2020	0.76	35.92	−0.07	5.23	−4.03	3.07	−3.00
2020–2021	1.68	38.57	0.59	0.67	−3.95	−0.16	0.40
2021–2022	1.07	9.70	−0.09	−14.22	−0.01	−0.94	1.49
Total	13.75	70.66	4.90	−5.70	9.56	7.71	17.67

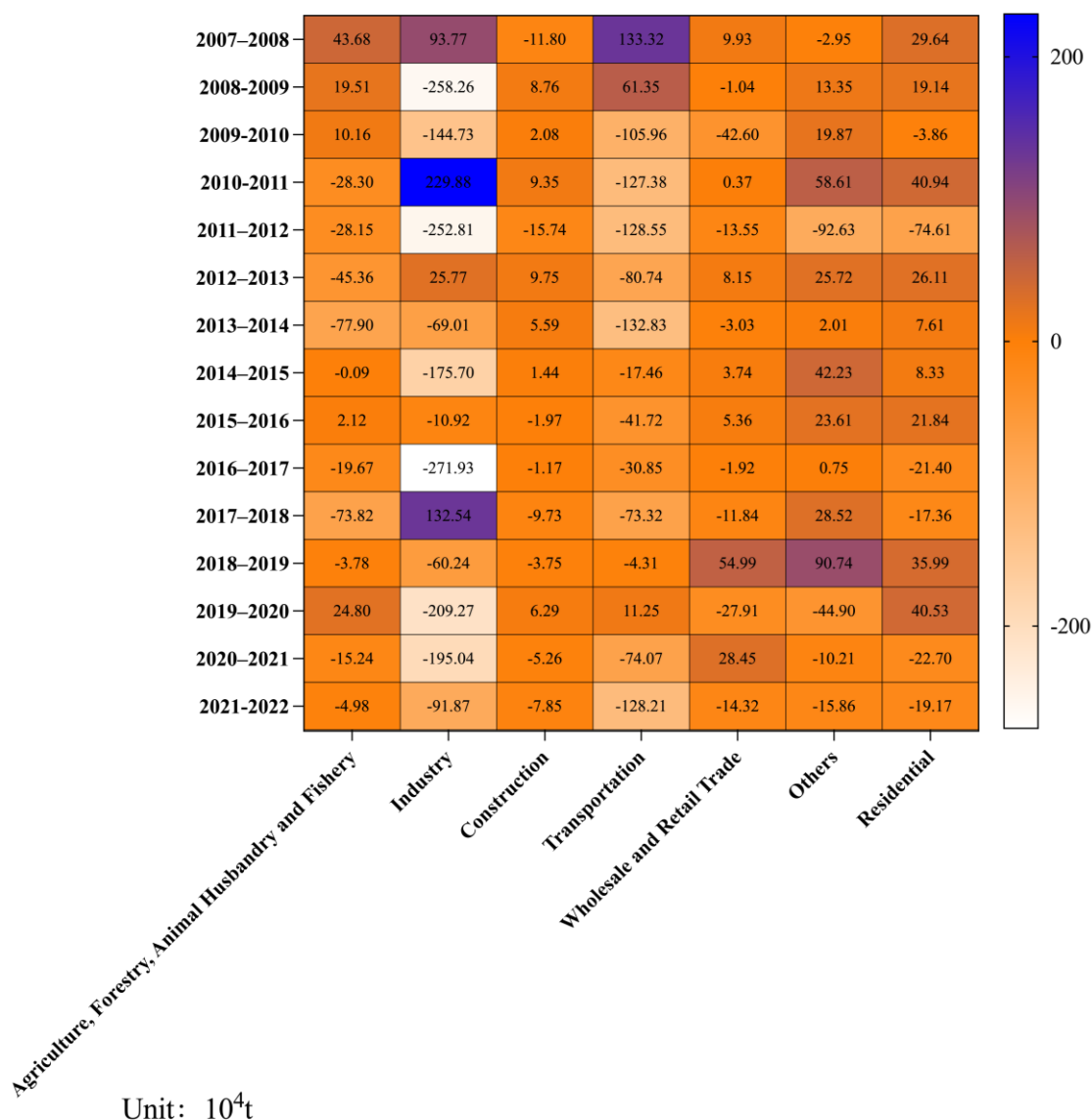


Figure 5. Energy intensity effect.

Table 3. Energy intensity effect.

Year	Agriculture, Forestry, Animal Husbandry and Fishery	Industry	Construction	Transportation	Wholesale and Retail Trade	Others	Residential
2007–2008	43.68	93.77	−11.80	133.32	9.93	−2.95	29.64
2008–2009	19.51	−258.26	8.76	61.35	−1.04	13.35	19.14
2009–2010	10.16	−144.73	2.08	−105.96	−42.60	19.87	−3.86

2010–2011	−28.30	229.88	9.35	−127.38	0.37	58.61	40.94
2011–2012	−28.15	−252.81	−15.74	−128.55	−13.55	−92.63	−74.61
2012–2013	−45.36	25.77	9.75	−80.74	8.15	25.72	26.11
2013–2014	−77.90	−69.01	5.59	−132.83	−3.03	2.01	7.61
2014–2015	−0.09	−175.70	1.44	−17.46	3.74	42.23	8.33
2015–2016	2.12	−10.92	−1.97	−41.72	5.36	23.61	21.84
2016–2017	−19.67	−271.93	−1.17	−30.85	−1.92	0.75	−21.40
2017–2018	−73.82	132.54	−9.73	−73.32	−11.84	28.52	−17.36
2018–2019	−3.78	−60.24	−3.75	−4.31	54.99	90.74	35.99
2019–2020	24.80	−209.27	6.29	11.25	−27.91	−44.90	40.53
2020–2021	−15.24	−195.04	−5.26	−74.07	28.45	−10.21	−22.70
2021–2022	−4.98	−91.87	−7.85	−128.21	−14.32	−15.86	−19.17
Total	−197.03	−1257.83	−14.01	−739.47	−5.21	138.86	71.03

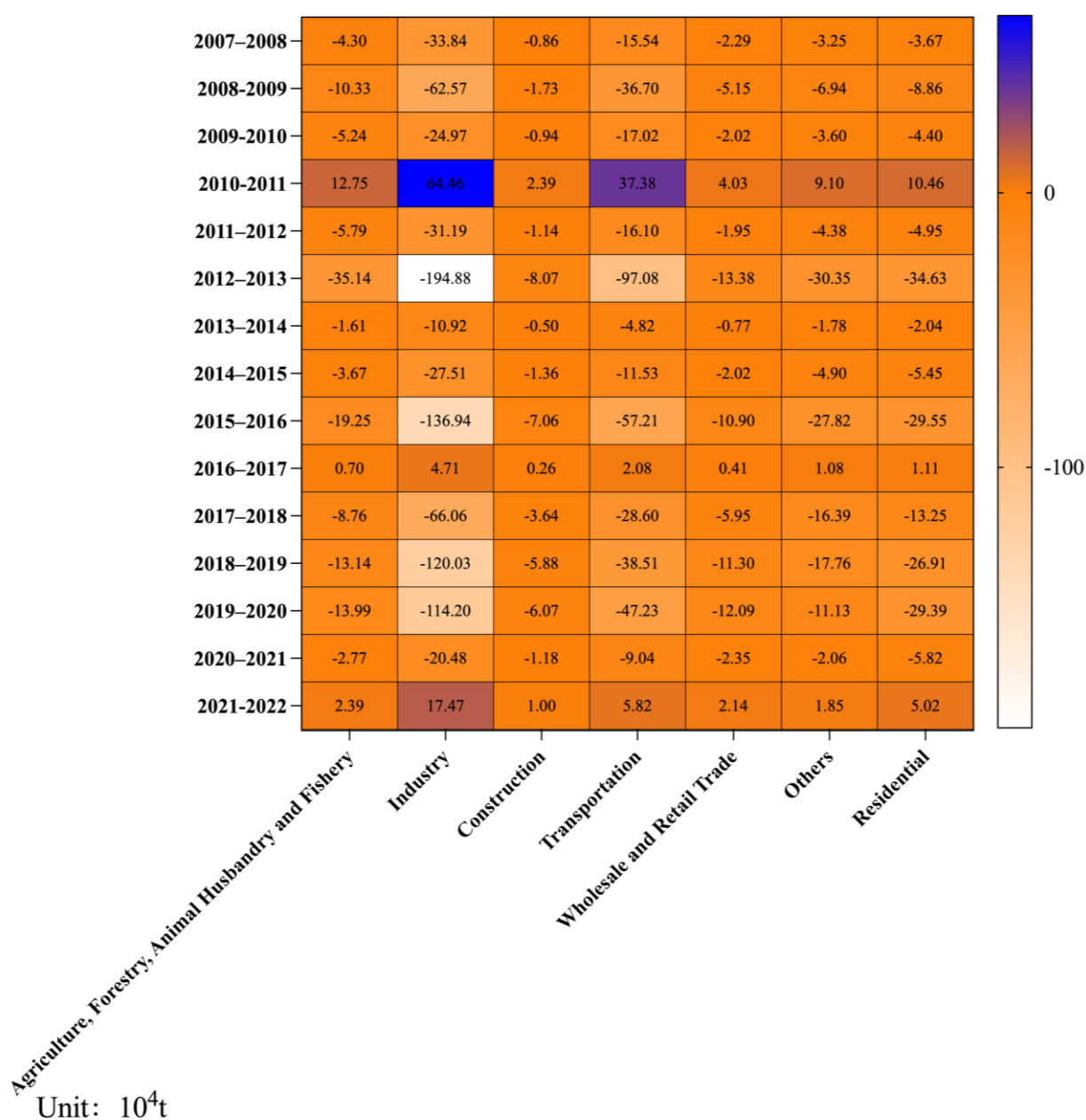


Figure 6. Industrial structure effect.

Table 4. Industrial structure effect.

Year	Agriculture, Forestry, Ani- mal Hus- bandry and Fishery	Industry	Construction	Transportation	Wholesale and Retail Trade	Others	Residential
2007–2008	−4.30	−33.84	−0.86	−15.54	−2.29	−3.25	−3.67
2008–2009	−10.33	−62.57	−1.73	−36.70	−5.15	−6.94	−8.86
2009–2010	−5.24	−24.97	−0.94	−17.02	−2.02	−3.60	−4.40
2010–2011	12.75	64.46	2.39	37.38	4.03	9.10	10.46
2011–2012	−5.79	−31.19	−1.14	−16.10	−1.95	−4.38	−4.95
2012–2013	−35.14	−194.88	−8.07	−97.08	−13.38	−30.35	−34.63
2013–2014	−1.61	−10.92	−0.50	−4.82	−0.77	−1.78	−2.04
2014–2015	−3.67	−27.51	−1.36	−11.53	−2.02	−4.90	−5.45
2015–2016	−19.25	−136.94	−7.06	−57.21	−10.90	−27.82	−29.55
2016–2017	0.70	4.71	0.26	2.08	0.41	1.08	1.11
2017–2018	−8.76	−66.06	−3.64	−28.60	−5.95	−16.39	−13.25
2018–2019	−13.14	−120.03	−5.88	−38.51	−11.30	−17.76	−26.91
2019–2020	−13.99	−114.20	−6.07	−47.23	−12.09	−11.13	−29.39
2020–2021	−2.77	−20.48	−1.18	−9.04	−2.35	−2.06	−5.82
2021–2022	2.39	17.47	1.00	5.82	2.14	1.85	5.02
Total	−108.14	−756.95	−34.77	−334.11	−63.59	−118.36	−152.33

Table 5. Economic output effect.

Year	Agriculture, Forestry, Ani- mal Hus- bandry and Fishery	Industry	Construction	Transportation	Wholesale and Retail Trade	Others	Residential
2007–2008	26.71	210.30	5.32	96.57	14.26	20.22	22.81
2008–2009	16.84	101.99	2.82	59.82	8.40	11.31	14.44
2009–2010	53.32	254.00	9.53	173.16	20.56	36.66	44.72
2010–2011	58.12	293.72	10.91	170.33	18.36	41.47	47.66
2011–2012	44.74	241.13	8.83	124.43	15.09	33.90	38.25
2012–2013	34.21	189.73	7.86	94.52	13.03	29.55	33.71
2013–2014	26.70	181.17	8.29	79.97	12.77	29.54	33.90
2014–2015	24.15	181.07	8.93	75.88	13.32	32.26	35.90
2015–2016	27.73	197.21	10.16	82.39	15.69	40.06	42.56
2016–2017	25.31	169.27	9.40	74.77	14.92	38.84	40.04
2017–2018	19.40	146.32	8.06	63.35	13.18	36.31	29.34
2018–2019	17.04	155.60	7.62	49.92	14.65	23.03	34.88
2019–2020	6.76	55.18	2.93	22.82	5.84	5.38	14.20
2020–2021	38.44	284.41	16.41	125.63	32.67	28.64	80.85
2021–2022	10.93	79.78	4.57	26.57	9.79	8.43	22.92
Total	430.38	2740.88	121.64	1320.14	222.52	415.60	536.18

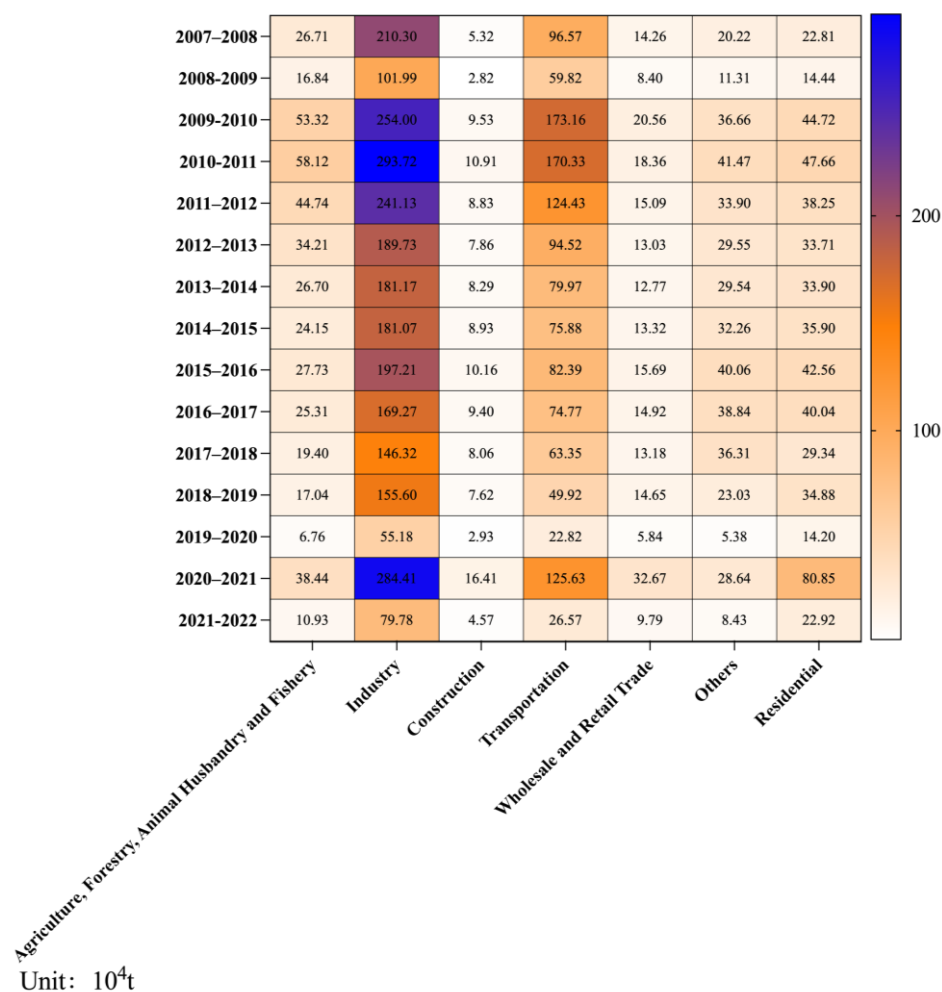


Figure 7. Economic output effect.

Table 6. Population size effect.

Year	Agriculture, Forestry, Animal Husbandry and Fishery	Industry	Construction	Transportation	Wholesale and Retail Trade	Others	Residential
2007–2008	3.01	23.71	0.60	10.89	1.61	2.28	2.57
2008–2009	3.71	22.47	0.62	13.18	1.85	2.49	3.18
2009–2010	4.88	23.26	0.87	15.86	1.88	3.36	4.10
2010–2011	4.11	20.78	0.77	12.05	1.30	2.93	3.37
2011–2012	−2.23	−12.02	−0.44	−6.20	−0.75	−1.69	−1.91
2012–2013	2.56	14.20	0.59	7.08	0.98	2.21	2.52
2013–2014	2.33	15.79	0.72	6.97	1.11	2.57	2.95
2014–2015	−2.58	−19.35	−0.95	−8.11	−1.42	−3.45	−3.84
2015–2016	−1.73	−12.32	−0.63	−5.15	−0.98	−2.50	−2.66
2016–2017	2.68	17.90	0.99	7.91	1.58	4.11	4.24
2017–2018	4.32	32.59	1.79	14.11	2.93	8.09	6.53
2018–2019	3.15	28.78	1.41	9.23	2.71	4.26	6.45
2019–2020	4.46	36.39	1.94	15.05	3.85	3.55	9.37
2020–2021	5.92	43.76	2.53	19.33	5.03	4.41	12.44
2021–2022	3.49	25.49	1.46	8.49	3.13	2.69	7.32
Total	38.07	261.43	12.27	120.68	24.80	35.31	56.64

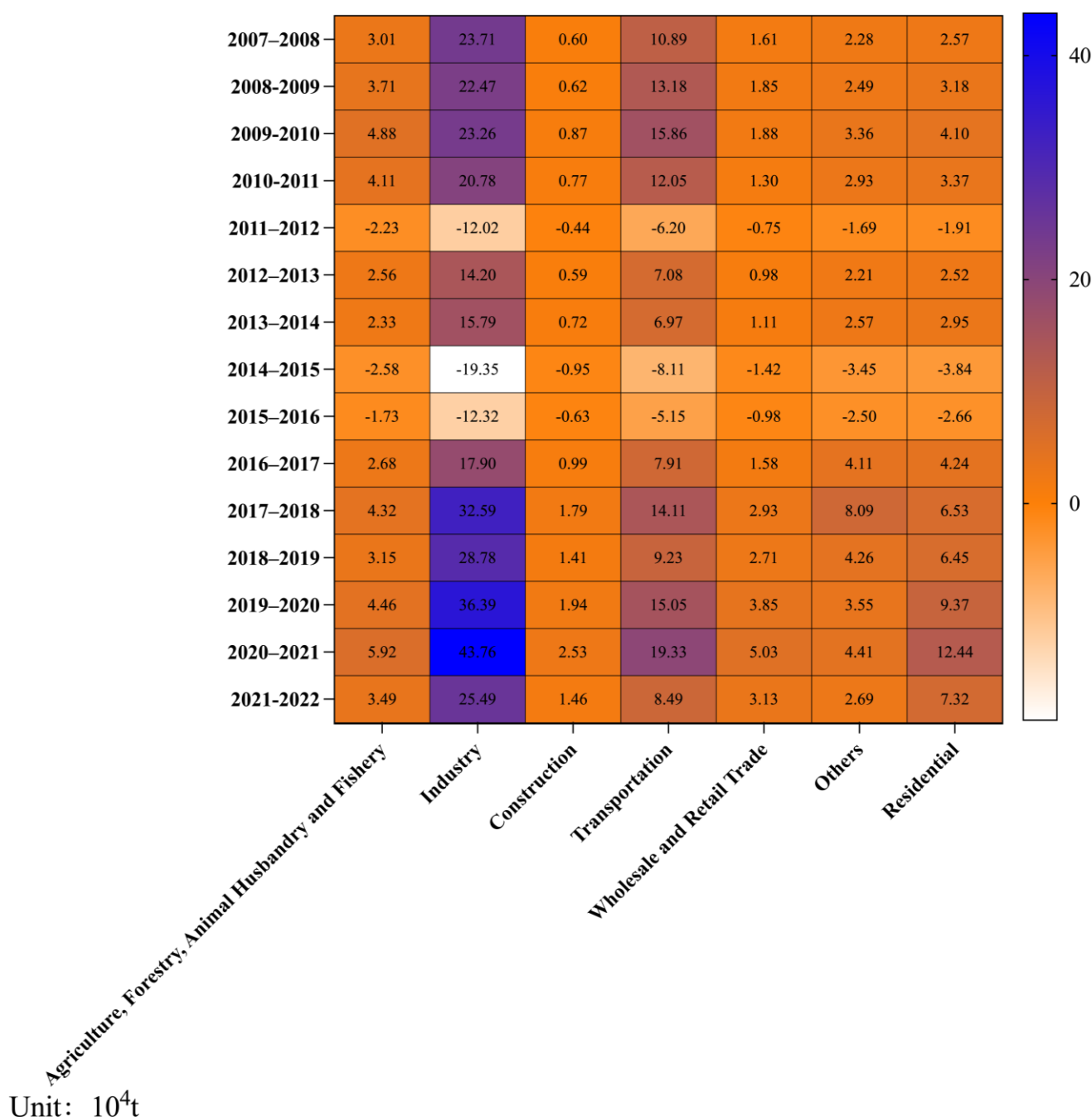


Figure 8. Population size effect.

3.3.1. Energy Structure

Figure 4 shows that energy structure has a positive effect on carbon emissions in the agriculture, forestry, animal husbandry, and fishery sector, the industrial sector, the construction sector, the wholesale and retail trade sector, and the residential sector, cumulatively increasing carbon emissions by 124.59×10^4 tonnes. In contrast, it has a negative effect only on the transportation sector. In the agriculture, forestry, animal husbandry, and fishery sector, diesel and electricity are the main energy sources. The combustion of diesel directly generates substantial carbon emissions, making it a direct source of emissions in agriculture. With the increasing level of agricultural mechanization, the widespread use of agricultural machinery (such as tractors, harvesters, and transport vehicles) directly consumes large amounts of diesel [48]. In terms of indirect carbon emissions, the

electrification of agricultural irrigation, cold-chain logistics, and agricultural product processing has led to continuous growth in electricity demand. In the industrial sector, Hainan's energy consumption structure is dominated by oil products, the combustion of which generates significant carbon emissions. Although Hainan leads the country in the share of clean energy installed capacity, there is still room for improvement in its power generation mix. In 2022, nuclear power accounted for the highest share of electricity generation in the country (28%), while renewable energy sources such as wind, solar, and hydropower together accounted for only 8% [49]. This means that every kilowatt-hour of electricity used by industry still has a considerable proportion generated from thermal power (coal-fired and gas-fired), thereby indirectly contributing to carbon emissions. In the residential sector, energy consumption from gasoline, LPG, and electricity promotes carbon emission growth. In the transportation sector, the reduction in carbon emission growth is mainly achieved through the vigorous promotion of new energy vehicles and the construction of a zero-carbon energy supply system.

3.3.2. Energy Intensity

Figure 5 shows that energy intensity has a negative effect on carbon emissions in the agriculture, forestry, animal husbandry, and fishery sector, the industrial sector, the construction sector, the transportation sector, and the wholesale and retail trade sector, while it has a positive effect on carbon emissions in the “other sectors” and the residential sector. In the agriculture, forestry, animal husbandry, and fishery sector, efficiency improvements have offset the carbon emissions caused by scale expansion [50]. First, through energy conservation and efficiency enhancement in production processes, such as promoting energy-efficient agricultural machinery and optimizing irrigation systems, direct energy consumption (diesel, electricity, etc.) per unit of agricultural output has been reduced. Second, the optimization of energy use patterns has shifted the sector from relying on fossil fuels to increasingly utilizing electricity, and actively exploring models such as agriculture, forestry, animal husbandry, and fishery sector thereby reducing carbon emissions at the source. Finally, the exploration of circular economy models has reduced energy extraction and consumption. In the industrial sector, it can be observed that more output is being produced with less energy: through technological progress and management optimization, energy efficiency in industrial production has been significantly improved. As a result, even though industrial output value is increasing, the total energy consumed and the carbon emissions generated do not increase proportionally, and may even decline. The province has cultivated 30 national-level green factories and 18 provincial-level green factories. Taking the Yangpu Economic Development Zone as an example, while its output value increased fivefold, energy consumption per 10,000 of value added decreased by 30%. In the construction sector, efficiency improvement is the key: through technological progress and management optimization, energy efficiency in green building construction has been significantly enhanced. This means that even as industry output grows, the total energy consumed and carbon emissions generated do not increase in tandem. In the transportation sector, with the increased adoption of new energy vehicles, energy consumption per unit of GDP has declined, thereby reducing carbon emission growth. In the wholesale and retail trade sector, energy conservation and emission reduction have been achieved mainly through energy savings in business premises, optimization of logistics and supply chains, and policy and market mechanisms. In the residential sector, the “rebound effect” comes into play: the “rebound effect” refers to the phenomenon where energy efficiency improvements (declining energy intensity) reduce the cost of use, thereby stimulating greater consumption. For example, after air conditioner efficiency

improves and electricity costs decrease, people may use air conditioners for longer periods, partially or even completely offsetting the emission reduction benefits brought by efficiency improvements [51].

3.3.3. Industrial Structure

As can be seen from Figure 6, the industrial structure factor has a negative effect on carbon emissions across all sectors. Among them, the negative effect on the industrial sector is the most pronounced, with a cumulative reduction of 756.95×10^4 tonnes of carbon emissions. In recent years, Hainan Province has promoted the green and low-carbon transformation of traditional industries, reducing the carbon emission intensity of existing industrial operations through technological upgrades and energy efficiency improvements. For instance, the province aims to reduce carbon emissions per unit of industrial value added by 65% from peak levels by 2045. It is actively developing low-energy, high-output industries such as the digital economy, offshore wind power, photovoltaics, and energy storage to optimize industrial structure at the source and lower overall carbon emission intensity. Furthermore, the province is establishing low-carbon and zero-carbon industrial parks to serve as benchmarks; these parks foster industrial agglomeration effects and facilitate centralized emission reductions. Efforts are also underway to promote low-carbon practices within the tertiary sector; for high-carbon-intensity service industries like tourism, measures such as promoting green hotels and green scenic areas are being implemented to reduce operational carbon emissions [52].

3.3.4. Economic Development Level

As shown in Figure 7, the economic output factor has a positive effect on carbon emissions across all sectors in Hainan Province. From 2007 to 2022, the cumulative contribution of the economic output effect amounted to 6173.17×10^4 tonnes. The industrial sector accounted for 2740.88×10^4 tonnes of this total, representing a share of over 48.32%. As a primary source of energy consumption and carbon emissions, the industrial sector saw growth in output value that directly drove up energy demand; furthermore, policies and financial support have continuously facilitated the expansion of industrial scale. The transportation sector contributed 1320.14×10^4 tonnes to the cumulative total. The development of the Hainan Free Trade Port has led to sustained, robust growth in shipping and aviation turnover. Additionally, rising per capita income has driven up private car ownership and travel frequency, both of which entail significant consumption of fossil fuels [53]. The residential sector contributed a cumulative 536.18×10^4 tonnes; as per capita GDP and urbanization rates have risen, living standards have improved, leading to increased demand for housing, home appliances, and automobiles, which has directly resulted in higher energy consumption for daily living. The construction sector contributed a cumulative 121.64×10^4 tonnes. Economic growth has driven the large-scale expansion of construction land, a land-use type identified as a major source of carbon emissions. Urban construction and infrastructure development are, by nature, activities characterized by high energy consumption and high emissions.

3.3.5. Population Size

According to the decomposition results of the LMDI model, the cumulative contribution of the population size effect from 2007 to 2022 was 585.82×10^4 tonnes. From 2007 to 2022, the impact of population size on carbon emissions was mainly positive, but the contribution was relatively small. The primary reason for this phenomenon is that population growth in Hainan Province has led to urban expansion, thereby increasing carbon emissions. This occurs mainly through the reduction in carbon sinks: encroachment on

ecological spaces weakens carbon sequestration capacity. Between 2010 and 2020, the forest area on Hainan Island decreased substantially by 2188.74 km². Additionally, an increase in high-emission human activities also contributed [54], as shown in Figure 8.

3.4. Analysis of the Decoupling Tapio Model

Table 7 presents the decoupling status between economic growth and carbon emissions from energy consumption in Hainan Province from 2007 to 2022. The period from 2007 to 2008 was characterized by an unfavorable “negative decoupling” state; during this time, carbon emissions rose rapidly year-over-year, while the Gross Regional Product (GRP) grew at a slower pace. From 2008 to 2010, the province exhibited a favorable “positive decoupling” state, indicating that carbon emission levels declined even as the economy expanded. The period from 2010 to 2011 saw a return to an unfavorable negative decoupling state, as the growth rate of carbon emissions surpassed that of the GRP after 2010. This interval coincided with the “12th Five-Year Plan,” a time when rapid economic expansion drove a surge in carbon emissions from energy consumption, resulting in serious ecological issues. From 2011 to 2022, the decoupling index fell from 1.43 to −0.13, reflecting a favorable positive decoupling state; this demonstrates the initial success of Hainan Province’s efforts to shift its economic development model from extensive growth prioritizing scale and speed to intensive growth prioritizing quality and efficiency, with a particular focus on upgrading the industrial structure.

Table 7. Decoupling level of economic growth and carbon emissions over time.

Time	$\Delta C/\%$	$\Delta G/\%$	E	Decoupling Status
2007–2008	0.31	0.20	1.58	Expansive negative decoupling
2008–2009	−0.02	0.10	−0.18	Strong decoupling
2009–2010	0.11	0.25	0.45	Weak decoupling
2010–2011	0.31	0.22	1.43	Expansive negative decoupling
2011–2012	−0.05	0.13	−0.37	Strong decoupling
2012–2013	0.00	0.12	0.04	Weak decoupling
2013–2014	0.04	0.11	0.42	Weak decoupling
2014–2015	0.04	0.08	0.44	Weak decoupling
2015–2016	0.02	0.10	0.22	Weak decoupling
2016–2017	0.01	0.10	0.11	Weak decoupling
2017–2018	0.06	0.09	0.70	Weak decoupling
2018–2019	−0.03	0.09	−0.37	Strong decoupling
2019–2020	−0.05	0.04	−1.04	Strong decoupling
2020–2021	0.10	0.17	0.58	Weak decoupling
2021–2022	−0.01	0.05	−0.15	Strong decoupling

3.5. Analysis of the Effects of Various Factors on the Decoupling Index

We selected representative one-year intervals (2007–2008, 2012–2013, 2017–2018, and 2021–2022) with a five-year spacing between them. Since the GDP growth rate is always positive (i.e., the denominator in the decoupling index is always greater than zero), the smaller the decomposition indicators, the greater the promoting effect on carbon emission decoupling. In the 2007–2008 period, the carbon emission decoupling index was mainly composed of the energy intensity effect and the economic output effect. In the decoupling model, the decoupling state is determined jointly by the economic growth rate, the carbon emission growth rate, and the decoupling index. As the GDP growth rate is always positive, a larger decoupling index indicates a less desirable decoupling state. Specifically, the energy intensity effect and the economic output effect inhibited the decline in the decoupling index, resulting in a weak decoupling state under their combined influence. In the

2012–2013 period, the energy structure effect did not change significantly and remained in a weak decoupling state, while the energy intensity effect decreased notably, changing the decoupling state from weak to strong decoupling. The industrial structure effect remained in a strong decoupling state. In 2017–2018, the economic output effect changed from an expansive coupling state to a weak decoupling state, indicating that with the improvement of emission reduction technologies, the growth rate of carbon emissions slowed down. The other effects all showed relatively desirable positive decoupling states. In 2021–2022, all effects exhibited positive decoupling states, among which the energy structure and energy intensity effects showed strong decoupling, indicating that the energy structure is continuously optimizing and the level of economic development is also rising. Overall, the main factors influencing carbon emission decoupling are energy intensity and economic growth; the decline in energy intensity promotes decoupling, while economic growth inhibits it [55], as shown in Table 8.

Table 8. Decomposition results of the carbon emission decoupling index by factors.

	Year	Energy Structure	Energy Intensity	Industrial Structure	Economic Output	Population Size
2007–2008	Decoupling index	0.01	0.69	−0.15	0.93	0.10
	ΔC	>0	>0	<0	>0	>0
	$\Delta TGDP$	>0	>0	>0	>0	>0
	Decoupling status	Weak decoupling	Weak decoupling	Strong decoupling	Expansive coupling	Weak decoupling
2012–2013	Decoupling index	0.06	−0.07	−0.90	0.88	0.07
	ΔC	>0	<0	<0	>0	>0
	$\Delta TGDP$	>0	>0	>0	>0	>0
	Decoupling status	Weak decoupling	Strong decoupling	Strong decoupling	Expansive coupling	Weak decoupling
2017–2018	Decoupling index	0.15	−0.06	−0.35	0.78	0.17
	ΔC	>0	<0	<0	>0	>0
	$\Delta TGDP$	>0	>0	>0	>0	>0
	Decoupling status	Weak decoupling	Strong decoupling	Strong decoupling	Weak decoupling	Weak decoupling
2021–2022	Decoupling index	−0.01	−1.23	0.16	0.71	0.23
	ΔC	<0	<0	>0	>0	>0
	$\Delta TGDP$	>0	>0	>0	>0	>0
	Decoupling status	Strong decoupling	Strong decoupling	Weak decoupling	Weak decoupling	Weak decoupling

4. Discussion

In terms of historical carbon emissions by energy type, our results are inconsistent with those of studies [4–8], which found that coal accounted for the largest proportion among the three major energy sources, further confirming the fundamental role of coal in China’s energy mix, consistent with China’s energy endowment of “abundant coal, scarce oil, and limited gas.” However, Hainan Province exhibits a high share of oil-based energy consumption. This can be explained by Hainan’s proximity to the South China Sea, where the northern part alone contains up to 10.6×10^6 tonnes of petroleum geological resources. In addition, Hainan is strategically located along major maritime shipping routes, with approximately 80% of China’s imported oil passing through its jurisdictional waters. This provides Hainan with natural advantages in the logistics, transshipment, and trade of oil and gas resources. Our results are consistent with study [9] regarding electricity consumption, which found that the share of primary electricity and other energy sources is growing

rapidly. Hainan's electricity consumption has also shown an increasing trend year by year, indicating that the rising proportion of electricity consumption is a concentrated reflection of its high-quality economic development, accelerated Free Trade Port construction, clean energy transition, and profound changes in lifestyle. In terms of total carbon emissions, our results differ from those of studies [10,11], which reported that total carbon emissions first increased and then decreased. In contrast, Hainan's total carbon emissions exhibited a pattern of first rising, then falling, and then rising again. Compared with these regions, Hainan's energy consumption structure still requires further transformation, with improvements in energy efficiency and a greater share of clean energy. With regard to sectoral carbon emissions, our findings are consistent with studies [7,16,17], which showed that carbon emissions from all sectors have increased year by year. The industrial sector, driven by its intensive and sustained fuel demand, constitutes the main source of end-use energy consumption emissions. The transportation sector ranks as the second largest source, attributable to Hainan's role as a Free Trade Zone and tourism island with substantial freight and passenger transport demand. The residential sector also shows increasing trend. The sectors with the largest carbon emissions, in descending order, are industry > transportation > residential.

In terms of influencing factors, the energy intensity effect and the economic output effect are the main factors exerting negative and positive effects on carbon emissions, respectively. Our results are consistent with study [56] regarding the GDP factor, but inconsistent with its findings on the energy intensity factor, which suggested that energy intensity promotes carbon emissions, whereas our results indicate that it inhibits emissions. This discrepancy may be because the regions studied in [57] have economic growth that relies heavily on extensive energy inputs, directly pushing up carbon emissions, whereas in Hainan, the energy consumption required per unit of GDP has been continuously declining. Our results are consistent with study [18] and others, which found that GDP and population factors are positively correlated with carbon emission growth. With social development and continuous regional GDP growth, local governments impose increasingly higher requirements on the scale and functionality of buildings. Regarding the population factor, population growth also leads to increased carbon emissions from the residential sector, thereby requiring more energy consumption. Our results are consistent with studies [6,13,14,19], which indicated that potential energy intensity and economic activity play roles in promoting and reducing emissions, respectively, while population size and energy structure have a positive but negligible impact on carbon emissions, and the industrial structure effect is relatively weak. Our results are inconsistent with study [7], which found that for carbon emissions from the industrial sector, economic output and industrial structure are the main negative and positive effects, respectively, while the inhibitory effects of energy structure and energy intensity are not significant, and population size has a certain positive effect. In contrast, our study shows that economic output has a negative contribution to the industrial sector, while energy intensity has a positive contribution, indicating that Hainan's energy consumption per unit of economic output is relatively low compared with other regions, and efforts should continue to be made to improve energy efficiency in the industrial sector.

In terms of decoupling effects, our results are consistent with study [58], which reported a favorable decoupling state between carbon emissions and GDP. Our study also shows a positive decoupling between carbon emissions and GDP, meaning that while the economy continues to grow, carbon emissions no longer increase in tandem. However, study [59] found that carbon emissions from the industrial sector are decoupled from economic output, with weak decoupling as the dominant state, whereas carbon emissions from residential energy consumption have not yet decoupled from consumption expenditure, and the decoupling state is unstable, without clear patterns of change.

Limitations and future prospects: This study could be improved upon by (1) expanding the study area and refining the spatial scale of analysis; (2) employing spatial models to better explain the spatial heterogeneity of regional carbon emissions and the influence of their driving factors, thereby laying a foundation for future research; (3) conducting sectoral analyses of decoupling effects in future studies; (4) adopting dynamic annual grid emission intensity factors; and (5) employing the latest dataset in the research. (6) Moreover, in future research, we will decompose the residential sector and the ‘other sectors’ separately from the other productive sectors. We will also redefine the sectoral activity variables. For productive sectors, value added can be used as the activity indicator. For the residential sector, population, household disposable income, floor area, or household consumption expenditure may be more appropriate. For the transport sector, if available, passenger-kilometers and freight turnover would be preferable.

5. Conclusions and Recommendations

5.1. Conclusions

We first established a carbon emission inventory for Hainan Province, categorized by energy type and economic sector, primarily utilizing the IPCC Greenhouse Gas Emission Factor Database. Subsequently, we employed the LMDI model and the Tapio decoupling index to analyze the factors influencing carbon emissions across sectors and the decoupling status between economic growth and carbon emissions. We further examined the contributions of changes in energy structure, energy intensity, industrial structure, economic output, and population size to the decoupling index. The main conclusions are as follows:

- (1) Overall, carbon emissions in Hainan Province showed an upward trend from 2007 to 2022, with an average annual growth rate of 5.75%. The fastest growth occurred between 2007 and 2011, a period characterized by rapid economic expansion and an industrial structure heavily reliant on the industrial sector and petroleum energy. Although the growth rate of carbon emissions slowed between 2012 and 2022, a significant spike of 9.84% (an increase of 4.2514 million tonnes) was recorded in 2021. By sector, the ranking of carbon emission shares from highest to lowest was: industry > transportation > residential > agriculture, forestry, animal husbandry, and fishery. The industrial sector accounted for the largest share of emissions, averaging 47.64% over the 2007–2022 period, reflecting its role as a pillar of Hainan’s economic development.
- (2) The decomposition results indicate that economic output, energy structure, and population size have positive effects on carbon emissions, while energy intensity and industrial structure have negative effects. At the sectoral level, the energy structure has a negative effect only on the transportation sector, and positive effects on all other sectors. The energy intensity factor has negative effects on all sectors except “other sectors” and the residential sector, with a cumulative contribution of 2003.65×10^4 tonnes of carbon emissions. The industrial structure factor has negative effects on carbon emissions across all sectors, with a cumulative contribution of 1568.23×10^4 tonnes. The economic output factor promotes emissions in all sectors, with a cumulative increase of 5787.35×10^4 tonnes, of which 2740.88×10^4 tonnes are from the industrial sector. The population factor also promotes emissions across all sectors, with a cumulative contribution of 549.21×10^4 tonnes.
- (3) Analysis using the Tapio decoupling model reveals that the period from 2007 to 2008 was characterized by an undesirable “negative decoupling” state. In contrast, the 2008–2010 period showed a desirable “positive decoupling” state, indicating that car-

bon emission levels declined alongside economic growth. The state reverted to undesirable negative decoupling between 2010 and 2011. From 2011 to 2022, the decoupling index fell from 1.43 to 0.13, reflecting a desirable positive decoupling state; this suggests that Hainan's efforts to shift its economic growth model away from extensive growth driven by scale and speed toward intensive growth driven by quality and efficiency have begun to yield results.

- (4) An analysis of how various factors affect the decoupling index identifies energy intensity and economic output as key drivers of carbon emissions. By combining the LMDI factor decomposition model with the Tapio model, the study analyzed the relationship between changes in carbon emissions (driven by specific factors) and the decoupling status of sectoral economic growth. The results show a desirable positive decoupling state regarding these factors during 2007–2008. However, during 2012–2013, energy intensity and economic output exhibited an undesirable negative decoupling state, whereas the period from 2017 to 2018 again demonstrated a desirable positive decoupling state. Throughout this timeframe, total carbon emissions initially decreased and then increased at a relatively slow pace, while the study area's Gross Regional Product (GRP) rose steadily, growing faster than in the initial period and outpacing the growth rate of carbon emissions. From 2021 to 2022, the impact of various factors on carbon emissions demonstrated a desirable "positive decoupling," indicating that as these factors developed positively, the rate of growth in carbon emissions declined.

5.2. Recommendations

- (1) Regarding the energy mix, efforts should be made to reduce reliance on oil-based energy, increase the share of renewable energy, and intensify R&D into clean energy substitution technologies. The proportion of electricity consumption in sectors such as agriculture, forestry, animal husbandry, and fishery; construction; transportation; and wholesale and retail trade should be increased. In terms of industrial structure, carbon emissions from energy consumption in Hainan Province primarily originate from the industrial sector, followed by the residential sector and transportation. Given the current situation, the Hainan provincial government should drive the low-carbon transition of key industries. For instance, it should accelerate low-carbon process innovation and digital transformation in the industrial sector and promote energy-efficient, low-carbon vehicles in the transportation sector. Residents should be encouraged to adopt green consumption habits, conserve energy, and purchase eco-friendly products.
- (2) Combining Hainan Free Trade Port's transportation carbon emission reductions with its rapidly expanding maritime and aviation freight characteristics, we aim to transform the enormous freight demand into a driving force for green transition. In the maritime sector, we are building green shipping hubs. Leveraging its unique Free Trade Port policies, Hainan is positioning core ports such as Yangpu Port as pioneers in green shipping. This involves promoting clean-energy vessels; constructing green ports; and optimizing the energy structure of ports. In the aviation freight sector, we are developing green aviation hubs. Hainan is taking advantage of its status as an international aviation hub to promote the green transformation of air cargo. Key measures include advancing the use of Sustainable Aviation Fuel (SAF), supported by the Free Trade Port policy advantages and the "Hainan Low-Carbon Island Construction Plan". By opening "green demonstration routes" and building relevant infrastructure, we can gradually expand SAF application. Additionally, we are fostering green airport-adjacent industries by establishing a green and low-carbon international cooperation demonstration zone in Jiangdong New Area, Haikou, to attract

enterprises in aviation technology, green new materials, and other sectors, thereby creating a green aviation industry cluster.

- (3) The mode of economic development should be transformed. Economic growth is a primary driver of rising carbon emissions. As Hainan accelerates its industrialization and urbanization, energy consumption, particularly the heavy use of fossil fuels, has surged, leading to a significant increase in carbon emissions.
- (4) Improvements should be made to population quality. Hainan Province should leverage its policy and energy advantages to formulate specialized plans for talent attraction and development. By fostering the local economy and providing diverse employment and business opportunities, the province can attract talent and increase population density, thereby fueling technological innovation and promoting high-quality regional development.

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