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Policy-Driven Development of Electric and Hydrogen Fuel Cell Vehicles for Low-Carbon Transition in Hainan Province

Yao Xiao[1], Caixia Yang[1], Hai Yang[1], Supannika Wattana[2], Buncha Wattana[2*]

[1] College of Electrical Engineering, Hunan Mechanical & Electrical Polytechnic, Changsha 410073, China
[2] Electrical and Computer Engineering Research Unit, Faculty of Engineering, Mahasarakham University, Maha Sarakham 44150, Thailand

Corresponding Author Email: buncha.w@msu.ac.th

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ABSTRACT

Hainan Province, rich in renewable energy resources, has implemented policies to promote electric vehicles (EVs) and hydrogen fuel cell vehicles (HFCVs), driving a green, low-carbon transformation. This study utilizes the Low Emissions Analysis Platform (LEAP) to analyze the impact of policy interventions on energy demand, CO_2 emissions, and energy costs in Hainan's transportation and electricity sectors, considering three scenarios: Baseline (BAS), Now Policy (NPS), and Advanced Policy (APS). The findings show that stringent policies reduce fossil fuel dependence, promote clean energy, and support sustainable development. The findings show that stringent policies significantly reduce fossil fuel dependence, promote clean energy adoption, and support sustainable development. By 2045, Hainan's total energy costs are projected to exceed $10 billion, with electricity costs comprising the largest share. Compared to BAS, the NPS and APS scenarios reduce transportation fossil fuel consumption by 10.3% and 12.7%, respectively; CO_2 emissions decrease by 5.0% in NPS and 9.6% in APS; and energy costs are lowered by $470.3 million under NPS and $660.9 million under APS. To promote the development of EVs and HCFVs, this study recommends accelerating their adoption, advancing clean energy transition, boosting renewable energy, setting carbon reduction targets, and optimizing clean energy investments.

1. INTRODUCTION

As global climate change accelerates, the adoption of electric vehicles (EVs) and hydrogen fuel cell vehicles (HFCVs) has become a crucial strategy for addressing environmental challenges and ensuring sustainable development [1]. China has formulated several strategic plans to drive the comprehensive green transformation of the automotive industry. The "New Energy Vehicle Industry Development Plan (2021-2035)" [2] sets the target that by 2025, new energy vehicles will account for about 20% of total new vehicle sales, with EVs becoming the mainstream in new car sales, public sector vehicles achieving full electrification, and fuel cell vehicles reaching commercial application. Meanwhile, the "Hydrogen Energy Industry Development Long-term Plan (2021-2035)" [3] positions hydrogen energy as a key industry, aiming to promote the deployment of 50,000 HFCVs by 2025, build multiple hydrogen refueling stations, and achieve an annual production of green hydrogen between 100,000 to 200,000 tons.

Hainan Province, located at the southernmost tip of China, has a tropical climate with abundant solar, wind and ocean energy resources [4]. The average annual sunshine duration exceeds 2,000 hours, with high solar radiation intensity. The coastline stretches over 1,900 kilometers, with stable wind speeds along the coastal areas. These advantages create a solid foundation for the growth of its new energy vehicle industry. In 2019, Hainan became the first province in China to announce a complete ban on the sale of fuel vehicles by 2030 [5]. In 2023, the Hainan Development and Reform Commission issued the "Hainan Province Hydrogen Energy Industry Development Plan (2023-2035) [6]." The plan outlines key milestones: by 2025, during the cultivation phase, hydrogen production will exceed 200,000 tons annually. By 2030, in the pilot phase, the number of HFCVs will reach 1,000, with renewable hydrogen production at 400,000 tons per year. By 2035, during the application phase, hydrogen energy will be widely adopted in transportation, chemicals, and energy sectors. In coordination with renewable energy generation, these strategies strive to optimize the energy structure and reduce CO_2 emissions. The number of EVs exceeded 190,000, representing 11% of all motor vehicles by the end of 2022. Additionally, more than 75,000 public and private charging piles (guns) have been established, creating a charging network that spans urban and rural areas and strongly supports green travel [7].

In light of this background, this study aims to analyze the impact of EVs and HCFVs on Hainan's transportation, electricity, and energy structure, while exploring strategies to overcome challenges in accelerating the green and low-carbon transition. The findings are intended not only to provide a scientific foundation for Hainan to meet its carbon peak and sustainable development goals but also to deliver practical insights for other island regions like Hainan navigating energy transformation and low-carbon pathways.

2. LITERATURE REVIEW

Research on the coordinated development of EVs and HFCVs remains limited. While some studies analyze both in parallel, they primarily focus on differences in economic feasibility, environmental impact, and technological aspects [8, 9]. Existing findings suggest that a complementary EVs and HFCVs development model could more effectively drive the low-carbon transition in transportation [10]. However, few studies have explored this integration in island or regional contexts, lacking an in-depth understanding of how coordinated policies can optimize deployment strategies and the interaction within energy systems.

In recent years, China's hydrogen energy industry has made significant strides. With abundant hydrogen resources, the country theoretically has the capacity to support approximately 100 million hydrogen fuel cell passenger vehicles annually. By 2019, over 40 hydrogen refueling stations had been built nationwide [11], and government subsidies for hydrogen fuel cell buses played a crucial role in phasing out high-emission vehicles [12]. However, despite HFCVs' currently low market share, policy adjustments and shifting consumer preferences are expected to accelerate their adoption [13]. Additionally, research highlights key factors influencing HFCV deployment, including cost, government subsidies, driving range, and hydrogen refueling infrastructure [14, 15]. Research highlights that cost, government subsidies, driving range, and hydrogen refueling infrastructure are key factors influencing HFCV deployment [14, 15], yet few studies have combined these factors with EV deployment to explore their synergies and trade-offs.

In Hainan, studies on energy transition and low-carbon development have also made significant contributions. The promotion of new energy vehicles and renewable energy generation has played a key role in reducing CO_2 emissions and improving the energy structure. For instance, Xiao et al. [16] estimated that banning fuel vehicle sales would increase electricity demand 20.22 times by 2025 and 47.30 times by 2030, compared to 2020, while greenhouse gas emission reductions would be constrained by the energy structure. He et al. [17] projected that NEV adoption could cut CO_2 emissions by 7.7 million tons by 2050. Li et al. [18] suggested that integrating photovoltaic-biomass hybrid renewable systems with EVs could address energy challenges. These studies provide valuable insights for Hainan Island's energy transition. However, these studies mainly focus on EVs or renewables alone and rarely analyze the coordinated development of EVs and HFCVs. Challenges such as power supply constraints, energy structure optimization, and policy implementation remain.

The Low Emissions Analysis Platform (LEAP) model has gained global recognition for its extensive use in analyzing energy demand, low-carbon energy systems, and greenhouse gas emission scenarios. One of its strengths is its ability to evaluate the benefits of EV adoption, as shown in studies from Thailand [19-21], China and the UK [22], and New Zealand [23]. However, LEAP's application to the field of HFCVs is relatively limited, with only regional studies in Qinghai Province [24] and Japan [25]. Particularly in island contexts, few studies use the LEAP model to assess the integrated impacts of EV and HFCV policies. This study aims to fill this gap by constructing various policy scenarios to evaluate the coordinated development of EVs and HFCVs in Hainan Province, analyzing their comprehensive effects on energy structure, economic benefits, and environmental outcomes.

Therefore, this study innovatively adopts a policy-driven approach to propose a pathway for the coordinated development of EVs and HFCVs. Using the LEAP model, it analyzes the impact of different policies on Hainan's energy structure, CO_2 emissions, and economy, providing theoretical support and policy recommendations for the low-carbon transition.

3. METHODOLOGY

3.1 Energy system model

The research primarily examines the comprehensive impacts of various policies on the transportation and electricity sectors. The energy system model for this paper is presented in Figure 1. Road transportation is classified into different categories based on fuel type and usage, including internal combustion engine passenger vehicles (ICEPV), electric passenger vehicles (EPV), natural gas passenger vehicles (NGPV), hydrogen fuel cell passenger vehicles (HFCPV), internal combustion engine freight vehicles (ICEFV), electric freight vehicles (EFV), hydrogen fuel cell freight vehicles (HFCFV), and natural gas freight vehicles (NGFV). All sectors, except transportation, consider only electricity demand. In transportation, trains are primarily powered by electricity, while air and water sectors rely on kerosene and residual fuel oil, respectively, with electricity demand also included. Additionally, this paper assumes that ICEVs operate on gasoline, while HFCVs run on diesel. The hydrogen considered is all green hydrogen, which refers to hydrogen produced by water electrolysis using renewable energy sources such as wind, solar, or hydropower.

3.2 Data consideration

Due to data update delays, the most complete data from 2022 is chosen as the base year. To ensure the stable progression of policies and technologies, 2045 is chosen as the end year.

3.2.1 Energy demand

Except for the road section of the transportation sector, electricity, kerosene, and residual fuel oil consumption from 2023 to 2045 is projected using polynomial regression model based on Hainan Province's Year Book (2013-2022) [26]. For the road section, the number of passenger and freight vehicles is estimated in a similar approach. Energy consumption for each vehicle type (E_i) is calculated using Eq. (1).

$$E_i = N_i \times F_i \tag{1}$$

where, E_i is the annual energy consumption of the i-th type of vehicle (unit: liters/year, kWh/year, kg/year). N_i is the number of vehicles of the i-th type (ICEPV, EPV, NGPV, HFCPV, ICEFV, EFV, NGFV, or HFCPV). F_i is the average of energy consumed per vehicle per year (unit: liters/vehicle/year, kWh/vehicle/year, kg/vehicle/year).

The average Fi for ICEPV, NGPV, ICEFV, and NGFV is determined from the Energy Balance (Physical Quantity) in the Year Book, as shown in Table 1. This dataset provides the annual consumption of gasoline, diesel, and natural gas in the transportation sector. By dividing the total fuel consumption by the corresponding number of vehicles, the average annual energy consumption per vehicle is obtained. For EVs and HFCVs, including EPV, HFCPV, EFV, and HFCFV, the Fi values are based on research data from references [27-30]. These studies provide the average annual electricity consumption (in kWh) or hydrogen consumption (in kg) per vehicle, taking into account factors such as average driving distance, energy efficiency, and the maturity of the respective technologies.

Total energy costs are derived from Eq. (2). The prices of different fuels are referenced from U.S. Energy Information Administration (EIA) and International Energy Agency (IEA). The price of hydrogen energy is 7 USD per kilogram [31].

$$Ci = Ei \times Pi \tag{2}$$

where, *Ci* is the total energy consumption cost for the i-th type of vehicle (unit: USD). *Pi* is the unit price of energy (unit: USD/liter, USD/kg).

3.2.2 Transformation

In the dispatching order, renewable energy generation is given the highest priority due to its zero direct CO_2 emissions and its crucial role in supporting carbon neutrality goals. This prioritization aligns with China's energy policy directives and international low-carbon development strategies. Following renewables, coal-fired and gas-fired power generation are dispatched based on their respective availability and cost-effectiveness. The average electrical loss is 5%. The CO_2 emission factor is based on IPCC standards. The lifespan, maximum availability, process efficiency, and costs are shown in Table 2.

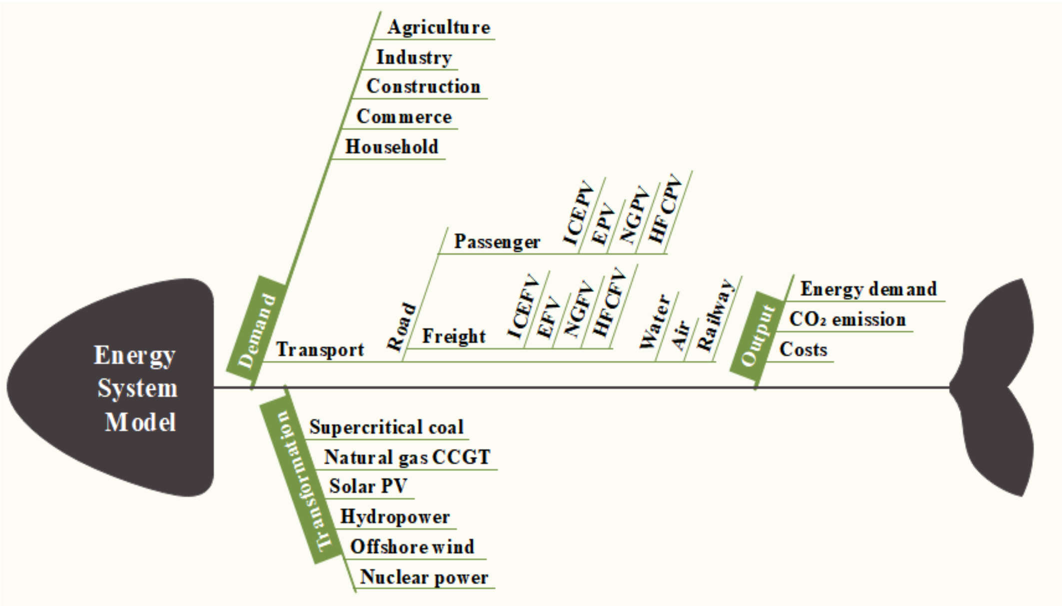


Figure 1. Energy model for transportation and power sectors

Table 1. The average Fi of different vehicle types [4, 27-30]

Vehicle Type	Fi	Vehicle Type	Fi
ICEPV (liters/vehicle/year)	500	ICEFV (liters/vehicle/year)	2000
EPV (kWh/vehicle/year)	1249	EFV (liters/vehicle/year)	7500
NGPV (tonnes of coal equivalent/vehicle/year)	4.8	NGFV (tonnes of coal equivalent/vehicle/year)	22
HFCPV (kg/vehicle/year)	55	HFCFV (kg/vehicle/year)	330

Table 2. Characteristics of technologies [32-38]

Technology	Life Time (year)	Maximum Availability (%)	Process Efficiency (%)	Capital Cost (USD/kW)	Fixed O&M Cost (USD/kW)	Variable O&M Cost (USD/MWh)	Fuel Cost (USD)
Supercritical coal	30	48.6	41	3,112	56.6	1.5	109.3/tons
Natural gas CCGT	30	48.6	41	1,049	71.8	2.3	0.4/m^3
Biomass power	30	20.0	40	2,149	47.9	3.0	-
Solar PV	30	12.5	20	435	14.4	2.0	-
Hydropower	50	13.5	80	1,793	37.7	3.3	-
Offshore wind	30	19.8	40	714	42.2	2.1	-
Nuclear power	30	76.2	90	4,000	60.0	2.0	8.0/MWh

Table 3. The capacities of different technologies

Technology	Coal	CCGT	Biomass	Solar	Hydropower	Wind	Nuclear
2022	5.0	2.5	0.5	2.5	1.5	0.3	2.2
2025	Ensure the fulfillment of electricity demand		0.7	6.5	1.5	2.0	2.5
2030			0.9	10.5	1.5	4.8	3.0
2045			1.8	23.0	1.5	16.0	4.5
2022			0.5	2.5	1.5	0.3	2.2

Table 4. The number of different vehicle types

Vehicle Type	Base Year	BAS		NPS		APS	
	2022	2030	2045	2030	2045	2030	2045
Passenger vehicles (thousand)	1,609	2,373	3,640	2,373	3,640	2,373	3,640
ICEPV	88.1%	68.3%	48.7%	44.8%	2.3%	44.8%	-
EPV	10.9%	30.7%	50.3%	54.5%	87.0%	54.0%	78.8%
NGPV	1.0%	1.0%	1.0%	0.7%	0.2%	0.7%	0.2%
HFCPV	-	-	-	-	10.5%	0.5%	21.0%
Freight vehicles (thousand)	203	295	460	295	460	295	460
ICEFV	92.8%	75.4%	45.0%	63.1%	3.6%	63.1%	-
EFV	6.3%	23.6%	54.0%	35.9%	74.5%	21.2%	49.8%
NGFV	1.0%	1.0%	1.0%	0.7%	0.2%	0.7%	0.2%
HFCFV	-	-	-	0.3%	21.7%	15.0%	50.0%

According to the Hainan Province Carbon Peaking Implementation Plan [39], by 2025, an additional 4 GW of solar power capacity and approximately 2 GW of wind power capacity will be installed. The share of non-fossil energy sources in the total installed capacity will reach 55%. By 2030, the proportion of installed capacity from non-fossil energy resources will increase to 75%. As the energy structure is optimized and adjusted, coal-fired power will gradually transition to gas-fired power. It is projected that by 2045, the ratio of installed capacity between coal-fired and gas-fired power will reach 1:2. This paper forecasts the installed capacity of various power generation technologies in Table 3.

3.3 Scenario development

This study constructs three development scenarios to analyze the coordinated evolution path of HFCVs and EVs in Hainan Province. The Baseline (BAS) scenario reflects the development trend under current technological and market conditions, the Now Policy Scenario (NPS) scenario considers the impact of existing policy initiatives, and the Advanced Policy Scenario (APS) scenario assumes more proactive policy support and technological advancements in the future. These scenarios represent potential development directions under varying policy intensities and technological progress, providing a comparative analysis for assessing the long-term development of the new energy industry in Hainan Province. The NPS is primarily designed from key policies, including the Medium- and Long-Term Action Plan for the Promotion of New Energy Vehicles in Hainan Province (2023-2030) [40], the Hainan Province Clean Energy Vehicle Development Plan [5], and the Hainan Province Hydrogen Energy Industry Development Plan (2023-2035) [6]. Based on these policies, it is assumed that the average annual scrappage rate for fuel-powered vehicles in Hainan Province will reach 15% after 2030. This assumption is supported by historical data on vehicle lifespan and scrappage patterns in China. Previous studies [41, 42] show that as vehicles approach their typical service life of around 10 to 15 years, the number of end-of-life vehicles increases rapidly, especially under strong regulatory pressure. Given that Hainan plans to completely ban the sale of conventional fuel vehicles by 2030 and aims to fully transition to clean energy vehicles, a 15% scrappage rate is a reasonable estimate that aligns with policy objectives. This rate reflects not only the natural aging of vehicles but also the accelerated phase-out of internal combustion engine vehicles driven by environmental policies and structural changes in the vehicle market. Hydrogen energy is initially promoted and adopted in freight vehicles. In the APS, it is assumed that the number of fuel-powered vehicles will reach zero by 2045. The price of hydrogen energy gradually decreases to \$3.5 per kilogram. The projected numbers of different vehicle types under various scenarios are presented in Table 4.

4. EMPIRICAL RESULTS AND DISCUSSIONS

This paper forecasts the impacts of different policies on the transportation and power sectors. Therefore, the results mainly analyze the energy demand of the transportation sector, the share of electricity generation from different technologies, various energy consumption levels, carbon dioxide emissions, and costs.

4.1 Energy demand of the transportation sector

Figure 2 illustrates the projected energy demand in the transportation sector under different scenarios from 2022 to 2045. Energy demand is expected to rise from approximately 2,800 KTOE in 2022 to around 5,000 KTOE in 2045, with notable variations across scenarios. By 2045, the NPS and APS scenarios reduce final energy demand by 559.1 KTOE (10.9%) and 503.6 KTOE (9.8%) respectively, compared to the BAS scenario (5119.07 KTOE), highlighting the significant impact of policy interventions on energy consumption. In 2022, the transportation sector was heavily dependent on conventional fossil fuels, which accounted for 97.1% of total energy consumption. Over time, this reliance gradually diminishes, with the share of fossil fuels declining to 90.2%, 79.9%, and 77.5% in the BAS, NPS, and APS, respectively, by 2045. Compared to BAS, the share of fossil energy consumption decreases by 10.3% and 12.7% in the NPS and APS, respectively. Notably, under the APS, as technological advancements accelerate and HFCVs gain wider adoption, demand for gasoline and diesel drops significantly, while electricity and hydrogen emerge as the dominant energy sources. Electricity demand fluctuates depending on the scale of EVs adoption. In the BAS, NPS, and APS, electricity consumption is 488.5, 724.8, and 612.9 KTOE by 2045, respectively. As policy stringency increases, the demand for traditional fossil fuels declines steadily, while the uptake of electricity and hydrogen energy sources grows substantially. This trend underscores the critical role of stringent policies and clean energy innovations in reducing dependence on fossil fuels and steering the transportation sector toward a more sustainable future.

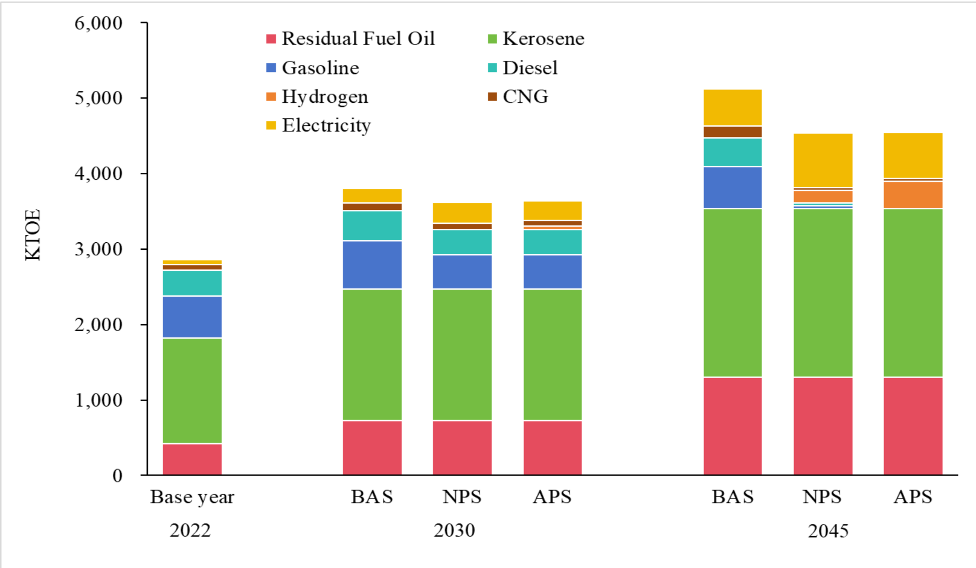
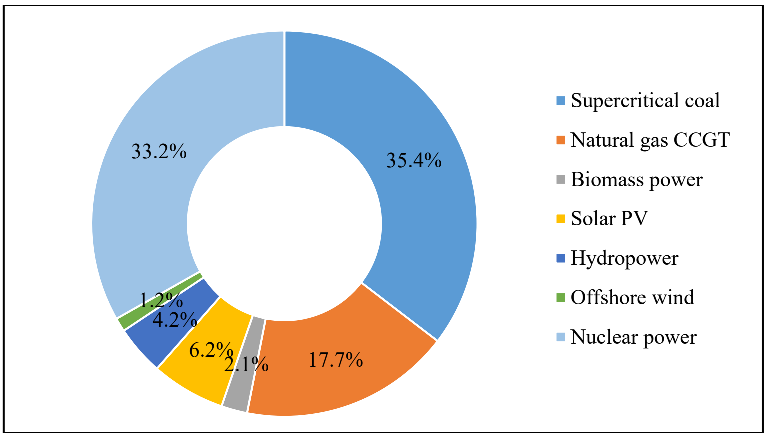
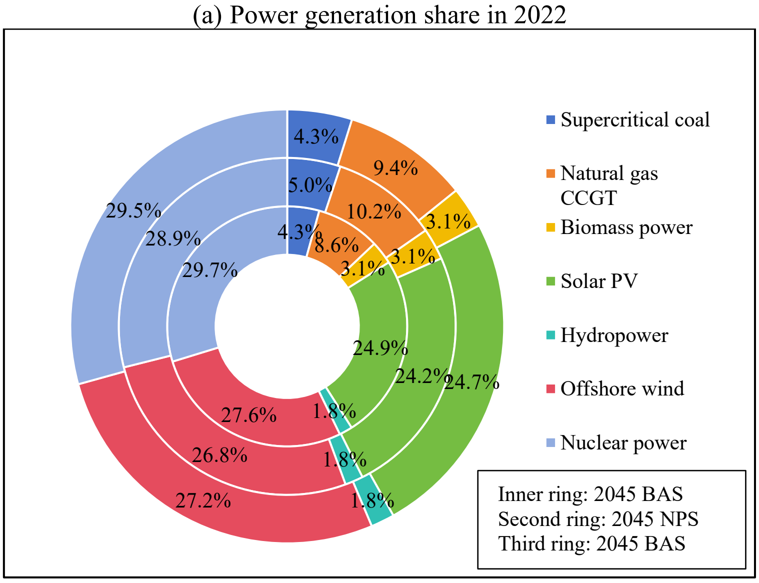


Figure 2. Energy demand in the transport sector from 2022 to 2035



(a) Power generation share in 2022



(b) Power generation share in 2045

Figure 3. Power generation shared by different technologies in 2022 and 2045

4.2 Electricity generation structure

Due to varying electricity demand across different policy scenarios, the corresponding power generation mix also differs. Figure 3 shows the shift in power generation shares by technology between 2022 and 2045, highlighting Hainan Province's transition toward clean energy. In 2022, coal and natural gas accounted for 53.1% of total power generation. By 2045, their combined share drops sharply to around 13%, reflecting a significant decline in fossil fuel reliance. In the NPS, where electricity demand is higher, the share of coal and natural gas is 2.3% greater than in the BAS, while in the APS, this share is 0.8% higher than in BAS, indicating that stricter policies further curb fossil fuel use. Wind and solar power drive the transformation of the energy structure. Their combined share surges from 7.4% in 2022 to over 50% in 2045, making them the dominant source of electricity. This shift signifies a fundamental transition in Hainan's energy landscape, characterized by the gradual phase-out of fossil fuels and a rapid expansion of renewable energies. Such a transformation not only reduces CO_2 emissions and fosters sustainable development but also establishes a solid foundation for a cleaner and more resilient energy system. Furthermore, it underscores the pivotal role of ambitious policies and technological advancements in accelerating the clean energy transition and securing a low-carbon future.

4.3 Total energy consumption

Figure 4 presents energy consumption trends across different scenarios. Total energy demand rises from 10,973 KTOE in 2022 to approximately 28,000 KTOE in 2045. Compared to the BAS, the APS and NPS achieve reductions of 476.2 KTOE and 306.5 KTOE, respectively. In 2022, traditional fossil fuels (coal, crude oil, natural gas, and CNG) accounted for 73% of total energy consumption. With stricter policies, their share declines to 27.4%, 26.3%, and 25.2% in the BAS, NPS, and APS, respectively, by 2045, while hydrogen sees substantial growth. Figure 5 further compares the 2045 energy mix, showing that the shares of renewable energy and nuclear power remain relatively stable across all scenarios. Compared to the BAS, crude oil consumption in the NPS and APS decreases by 1,034.2 KTOE and 956.1 KTOE, respectively, while hydrogen consumption increases by 167.0 KTOE and 365.8 KTOE. Meanwhile, natural gas and coal consumption rise by 606.5 and 318.7 KTOE in the NPS and APS. The increase in electricity demand leads to a corresponding rise in fossil fuel consumption. However, with the optimization and adjustment of the energy structure, the proportion of coal-fired power gradually decreases, while natural gas power generation increases. In contrast, under the APS scenario, a higher share of HFCVs results in relatively lower overall electricity demand, leading to a smaller increase in natural gas power generation. This indicates that during the energy transition process, adjustments in the energy structure under different scenarios significantly impact the demand for various fossil fuels. Although total electricity demand rises, optimizing the energy mix and increasing the share of clean energy can effectively control coal usage and utilize natural gas as a flexible transitional energy source. Meanwhile, the promotion of hydrogen vehicles helps reduce overall electricity demand, thereby alleviating the growth pressure on natural gas power generation and achieving a cleaner and more sustainable energy development pathway. Strengthening clean energy initiatives not only curtails fossil fuel dependence but also accelerates Hainan's transition toward a low-carbon and sustainable energy system.

4.4 CO_2 emission

From 2022 to 2045, CO_2 emissions in Hainan Province follow a trajectory of a slight initial increase, peaking around 2030, before gradually declining. The effectiveness of different scenarios in reducing emissions is significant (Figure 6). As shown in Table 5, under the BAS, emissions increase marginally from 24.7 million tons of CO_2 in 2022 before declining to 21.9 million tons by 2045. In the NPS, emissions fall to 20.8 million tons, a 5.0% reduction from BAS, while the APS achieves a more substantial decline to 19.8 million tons, 9.6% lower than BAS. By sector, the power industry sees the most significant emissions reduction, driven by a growing share of renewable energy. Emissions drop sharply from 16.3 million tons in 2022 to 7.8 million tons (BAS), 9.5 million tons (NPS), and 8.7 million tons (APS) by 2045, underscoring the pivotal role of clean energy in emissions mitigation. In contrast, the transportation sector follows an upward trajectory. Due to the limited consideration of energy transitions in air and water transport, emissions rose from 8.4 million tons in 2022 to 14.1 million tons (BAS), 11.3 million tons (NPS), and 11.1 million tons (APS) in 2045. Despite advancements in EVs and HFCVs, the sector still faces considerable challenges in lowering emissions. The APS achieves the highest emission reductions, demonstrating the effectiveness of stringent policies. However, persistently high transportation emissions indicate a need for stronger interventions. Accelerating EVs and hydrogen infrastructure deployment, enforcing stricter energy transition policies, and promoting sustainable development in air and water transport will be essential for achieving deeper carbon reductions.

4.5 Costs of transport and electricity sector

Costs of transport and electricity sector include transport fuels, electricity fuels, and other electricity costs in this study. "Other electricity costs" refer to capital cost, fixed O&M cost, and variable O&M cost. The costs in Hainan Province rise significantly, with total expenditures increasing from $4,874.5 million in 2022 to over $10,000 million across all scenarios by 2045 (Figure 7). As depicted in Table 6, the BAS incurs the highest cost at $11,026.0 million, while NPS and APS reduce expenditures by $470.3 million and $660.9 million, respectively, highlighting the economic advantages of stricter policies. Transport fuel costs surge under BAS, reaching $5,034.9 million in 2045, whereas NPS and APS lower these costs by $754.2 million and $806.8 million, driven by the adoption of EVs and HFCVs as well as declining hydrogen costs. Meanwhile, electricity fuel costs decrease slightly, with BAS achieving the lowest level at $1,370.4 million by 2045, reflecting a shift toward cleaner energy sources. However, other electricity-related costs rise significantly due to infrastructure investments, reaching $4,620.7 million (BAS), $4,660.2 million (NPS), and $4,645.7 million (APS) in 2045. NPS and APS effectively control long-term cost growth, particularly in transport fuels, underscoring the importance of sustained clean energy investments and policy interventions to balance economic and environmental goals.

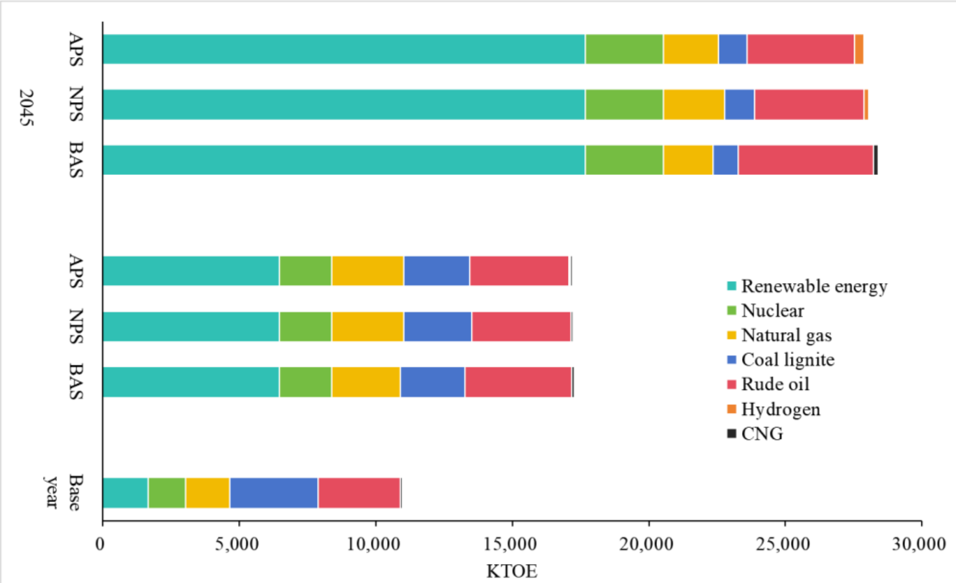


Figure 4. Total energy consumption over the period 2022-2045

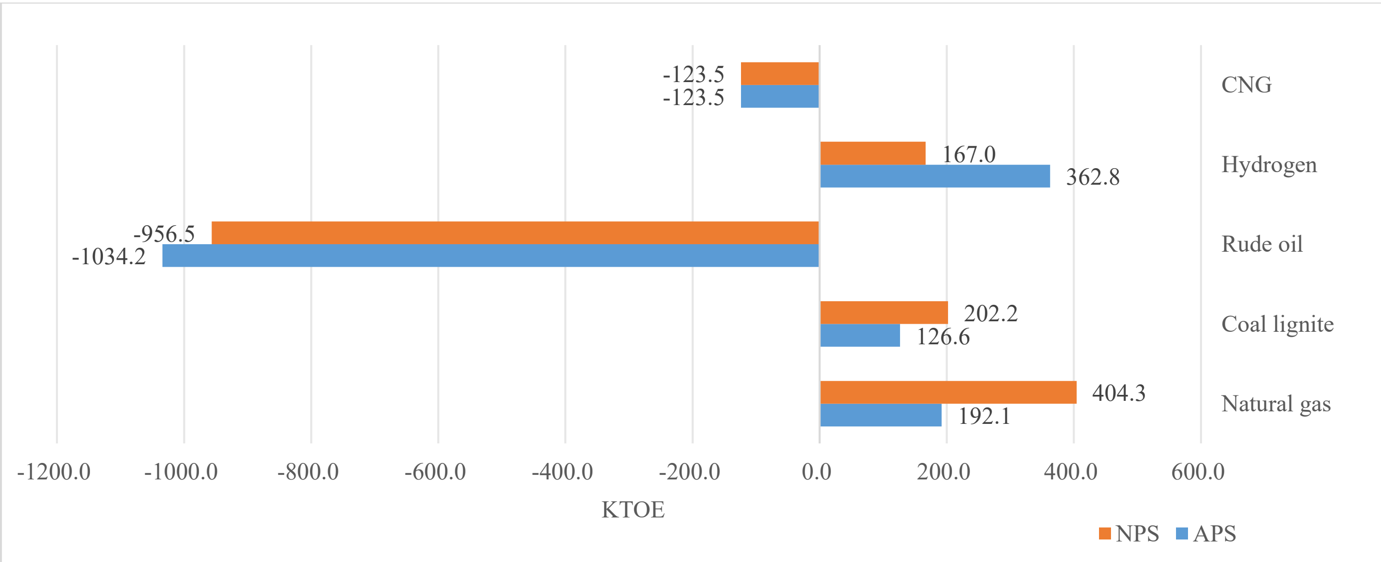


Figure 5. Changes in energy consumption by energy types in 2045

Note: This figure illustrates the changes in energy consumption by energy types in 2045, comparing the NPS and APS with the BAS.

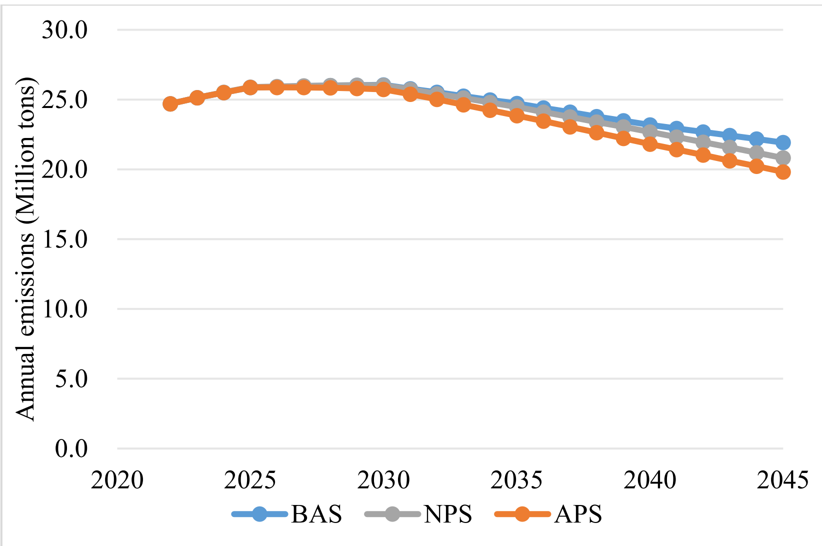


Figure 6. The change of CO_2 emission for the period of 2022-2045

Table 5. Annual emissions from electricity generation and transport sectors for different scenarios

Annual Costs (million USD)	2022	2030			2045		
	Base Year	BAS	NPS	APS	BAS	NPS	APS
Transport fuels	2,585.9	3,659.6	3,322.5	3,409.0	5,034.9	4,280.7	4,228.1
Electricity fuels	1,480.6	1,877.6	1,962.8	1,951.6	1,370.4	1,614.8	1,491.3
Other electricity costs	808.0	2,008.7	2,010.9	1,994.7	4,620.7	4,660.2	4,645.7
Total	4874.5	7545.9	7296.2	7355.3	11026.0	10555.7	10365.1

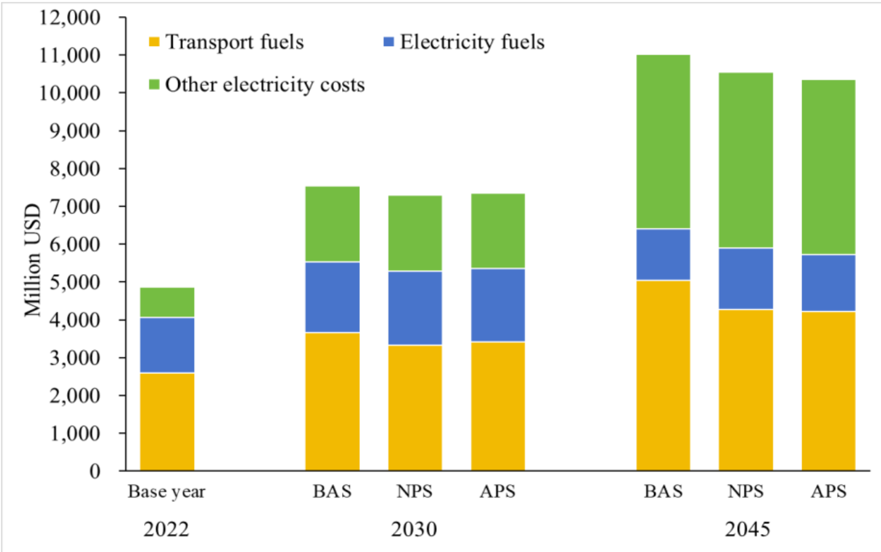


Figure 7. Annual costs for the period of 2022- 2045

Table 6. Annual costs from transport fuels, electricity fuels, and other electricity costs for different scenarios

Annual Emissions (million tons)	2022	2030			2045		
	Base year	BAS	NPS	APS	BAS	NPS	APS
Electricity generation	16.3	15.1	15.9	15.6	7.8	9.5	8.7
Transport	8.4	11.0	10.2	10.2	14.1	11.3	11.1
Total	24.7	26.1	26.1	25.8	21.9	20.8	19.8
Change from BAS (%)	0	0	0	-1.1	0	-5.0	-9.6

5. POLICY IMPLICATIONS

The analysis reveals that compared to the BAS, CO_2 emissions in the APS are reduced by 9.6% and costs by 660.9 million USD. This highlights the importance of effective policies, technological advancements, and widespread clean energy adoption for achieving sustainable development, reducing CO_2 emissions, and controlling long-term energy costs.

To optimize the implementation of policies, several challenges need to be addressed. For EVs, driving range is a key factor influencing market acceptance, despite advancements in battery technology [43]. Moreover, charging infrastructure is insufficient, particularly in remote areas like Wuzhishan and Qiongzhong. The environmental impact and lifecycle of batteries also require effective recycling and disposal solutions as EV adoption grows. In contrast, HFCVs offer advantages in driving range, refueling speed, and performance in low temperatures. However, HFCVs in Hainan are still in the early development stages, with inadequate infrastructure and no large-scale hydrogen refueling station network [44]. Challenges include a lack of site selection and approval standards, reliance on imported core equipment, high costs, and weak safety regulations. Key technologies in storage and transportation require further breakthroughs, and hydrogen pipeline infrastructure is yet to be scaled in Hainan. Additionally, the cost of HFCVs remains prohibitive, with prices ranging from 2-5 times higher than gasoline vehicles and 1.5-2.5 times higher than EVs [45, 46].

The following key policy recommendations are proposed:

1) Promoting EVs and HFCVs development.

Short-term goals (by 2025): Ultra-fast charging stations should be deployed along the Ring Road and the eastern/western highways to reduce charging time to 10-15 minutes, complemented by photovoltaic canopies for integrated solar-storage-charging solutions [47]. Wireless charging parking lots should be introduced in key tourist destinations such as Sanya and Wanning, while remote mountainous areas should pilot battery-swapping stations to mitigate range anxiety. A unified provincial charging app should integrate real-time charging station data, offering dynamic pricing and reservation services. Drawing on Zhejiang Province's experience [48], Hainan should prioritize hydrogen adoption in public transport, focusing on urban buses and tourist shuttles. A hydrogen refueling station along the Haikou-Sanya eastern expressway should support hydrogen-powered heavy-duty trucks transporting duty-free goods, with an annual $14,000 subsidy per vehicle.

Mid-term goals (by 2030): A hybrid model combining smart charging stations with battery-swapping systems is recommended [49]. A 500 MW offshore wind power project near Dongfang City and Lingao County, coupled with water electrolysis, should target an annual green hydrogen output of 20,000 tons by 2027. Furthermore, Hainan should collaborate with ASEAN nations to publish the White Paper on Hydrogen Energy Technology in Tropical Regions and lead the development of international standards for hydrogen storage and transportation in high-temperature, high-humidity environments. Electrolysis-based hydrogen production should be integrated with renewable energy to enhance green hydrogen sustainability [50, 51].

Long-term goals (by 2045): EPVs are expected to comprise 78.8% of the market, while HFCFVs aim to reach 50%. On Yongxing Island in Sansha City, a wind-solar-hydrogen storage microgrid should replace diesel generators, cutting off-grid energy costs by 40%. Green financial instruments, including green bonds and low-interest loans, should be leveraged to drive investment and innovation, accelerating hydrogen energy commercialization [52].

2) Expediting the transition to clean energy in transportation.

Short-to-Mid Term Goals (2025-2030): Gradually strengthen restrictions on the purchase and scrappage policies of fuel vehicles, and formulate a concrete implementation roadmap for banning the sale of fuel vehicles by 2030. Policies should also promote the adoption of sustainable fuels and technologies in aviation and shipping, including biofuels, hydrogen, and electrification, to address emissions challenges in these sectors. A 30% subsidy could be offered for fishing boats and ferries, alongside shore power facilities at ports to cut fisheries-related carbon emissions. By 2030, 50% of international cruise ships docking at Sanya Phoenix Island must use hydrogen fuel, supported by liquid hydrogen refueling infrastructure.

Long-term goal (2045): Completely phase out conventional fuel vehicles, achieve full clean energy substitution in aviation and shipping, and establish a low-carbon transportation system.

3) Transforming the power sector through renewable energy.

Hainan should enhance the development of large-scale photovoltaic and offshore wind power projects, attracting investment through streamlined approval processes, land access, and tax incentives. Simultaneously, encouraging the installation of rooftop photovoltaic systems by residents and businesses [53], with a "self-consumption, surplus to the grid" model, will reduce upfront costs. To address stability challenges as renewable energy share grows, the government should invest in smart grids and energy storage technologies [54], advancing the digitalization and modernization of the grid to ensure efficient energy management. For every ton of green hydrogen consumed, enterprises can exchange it for 2-5 tons of carbon credits, which can be traded at the Hainan International Carbon Emissions Trading Center.

4) Strengthening policy stringency for emission reduction targets.

Hainan should set phased carbon emission reduction targets. The power sector should prioritize renewable energy deployment to achieve carbon peaking by 2030, while the transportation sector should focus on electrification and hydrogen applications, with carbon peaking set for after 2030. Introducing carbon pricing mechanisms or emissions trading systems will incentivize businesses to reduce carbon footprints and generate revenue for clean energy investments [55].

5) Balancing economic and environmental goals.

The study shows that stricter policies (such as NPS and APS) not only reduce CO_2 emissions but also lower long-term energy costs. Policymakers should prioritize cost-effective clean energy investments and support ongoing research into advanced technologies for batteries, hydrogen production, storage, and transportation. The European Extended Producer Responsibility (EPR) system [56] can serve as a model for battery recycling, holding manufacturers accountable for collection, recycling, and disposal. These policy measures will provide critical support for Hainan's sustainable development, fostering a successful transition to a green, low-carbon economy.

6. CONCLUSIONS

This study highlights the pivotal role of policy interventions in shaping energy demand, CO_2 emissions, and energy costs in Hainan's transportation and energy sectors through predictive analysis of various policy scenarios. Using the LEAP software platform, three scenarios were developed: BAS, NPS, and APS. The findings demonstrate that stringent policies significantly reduce fossil fuel dependence, promote clean energy adoption, and foster sustainable development. With the widespread adoption of EVs and HFCVs, the demand for oil and diesel will gradually decrease, and electricity and hydrogen will become the primary energy sources. In terms of power generation, Hainan's energy structure is expected to undergo a significant transformation, with the share of coal and natural gas in power generation dropping from 53.1% in 2022 to approximately 13% by 2045. Meanwhile, the share of wind and solar energy will increase from 7.4% to over 50%, becoming the dominant sources of electricity. CO_2 emissions are expected to peak in 2030 and decline thereafter, particularly in the power sector, where emissions will decrease significantly as renewable energy share increases. However, the transportation sector continues to face challenges, with emissions rising, underscoring the need for accelerated energy transition in transportation. Energy costs are projected to exceed \$10 billion by 2045, with transportation fuel costs taking the largest share. The NPS and APSs show that policy interventions effectively control energy costs, especially in transportation fuels, yielding substantial long-term savings. In the APS, fossil fuel consumption in the transportation sector drops by 12.7% by 2045, coal and natural gas share in power generation increases by 0.8%, CO_2 emissions fall by 9.6%, and energy expenditure is reduced by \$660.9 million compared to the BAS.

Based on these findings, the study proposes several policy recommendations: (1) Accelerate the adoption of electric and HFCVs, with a focus on hydrogen applications in public transportation; (2) Facilitate the clean energy transition in transportation by phasing out gasoline and diesel vehicles and promoting sustainable fuels in aviation and shipping; (3) Boost renewable energy development, encourage rooftop photovoltaic installations, and support smart grid infrastructure; (4) Set phased carbon emission reduction targets, prioritizing carbon peaking in the energy and transportation sectors; (5) Focus on cost-effective clean energy investments that balance economic growth with environmental goals. These recommendations provide crucial guidance for Hainan's sustainable development, aiming to reduce CO_2 emissions while maintaining economic growth and energy security, and enabling a successful transition to a green, low-carbon economy.

Future research should address the technological bottlenecks Hainan faces in its energy transition, assess the long-term impacts of various policies on regional economic and social development, particularly regarding the potential of green finance, energy storage, and smart grid integration. Additionally, studies should explore Hainan's role in global climate governance and promote international collaboration to facilitate energy technology exchange, contributing to the global green and low-carbon transition.

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