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Air quality benefits of an accelerated transition to new energy vehicles in Hainan Province, China

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INTRODUCTION

Protecting the environment is a key priority for the government of Hainan. The island province in the southernmost part of China was named an Ecological Civilization Pilot Zone in 2019. Accordingly, Hainan envisions itself as being a world leader in environmental quality by 2035.[1] Its economic development plan as China's largest free trade port also emphasizes environmental protection.[2]

Safeguarding and improving air quality is an important part of these environmental efforts. Although Hainan has some of the best air quality among all of China's provinces, further efforts are required to meet World Health Organization air quality guidelines. Hainan's 2022 annual average ambient fine particulate matter ($PM_{2.5}$) concentration was 12 micrograms per cubic meter of air ($\mu g/m^3$), better than the

1 Di Zhou and Yang Yang, 沈晓明: 到2035年, 海南岛的生态环境要做到世界领先 [Shen Xiaoming: Hainan island is to be a world-leading ecological environment by 2035], *The Paper*, April 12, 2021, https://www.thepaper.cn/newsDetail_forward_12156412.

2 海南自由贸易港建设总体方案 [The Central Committee of the Communist Party of China and the State Council issue the overall plan for the construction of Hainan Free Trade Port], *Xinhua News Agency*, June 1, 2020, http://www.gov.cn/zhengce/2020-06/01/content_5516608.htm.

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average annual 18 μg/m^3 target for 2020–2035 laid out in the Ecological Civilization Pilot Zone plan, and the annual average ozone concentration was 112 μg/m^3 in 2022.[3] However, World Health Organization guidelines call for no more than 5 μg/m^3 for $PM_{2.5}$ and no more than 100 μg/m^3 for ozone.[4] Therefore, for Hainan to achieve a world-leading environment for air quality, additional actions are needed.

Hainan also has ambitious plans to develop a clean road-transport sector, as outlined in the provincial government's Clean Energy Vehicle Development Plan, released in 2019.[5] The plan put forth a roadmap for light-duty vehicles and buses that culminates with a target allowing only new energy vehicle (NEV) or natural gas-powered new vehicle sales in 2030.[6] In July 2023, the provincial government published a Mid- to Long-Term Action Plan on New Energy Vehicle Deployment (2023–2030), further increasing sales targets for most vehicle segments to 100% NEVs.[7]

Successful widespread adoption of NEVs will reduce tailpipe emissions of carbon dioxide (CO_2) and other pollutants. In our 2022 vehicle emissions inventory study, we modeled the impact of tailpipe CO_2 emissions from Hainan's road-transport sector under current policies and under an accelerated transition to NEV.[8] We found that Hainan's Clean Energy Vehicle Development Plan—the guiding policy roadmap for Hainan's road-transport sector between 2019 and 2023—was insufficient for CO_2 emissions to peak by 2030 before starting to decline. Therefore, Hainan would not meet the timeline pledged by the Chinese government.[9] Conversely, an accelerated transition to NEVs will help Hainan meet the Chinese central government's goal of peaking CO_2 emissions by 2030.

This report, which builds on our previous research, explores the air quality impacts of an accelerated transition to NEVs and how it can help Hainan achieve its progressive air quality goals.

METHODOLOGY AND DATA

The overall methodology of this study is illustrated in Figure 1. The Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC), developed by Tsinghua University, was used to develop our background emissions inventory. This inventory provides data on emissions generated in 2020 by different sectors in China, including power, agriculture, industry, and transportation. The MEIC emissions data

3 Ecological Environment Monitoring Center of Hainan Province, 2022年海南省生态环境状况公报 [Bulletin of Ecological and Environmental Status of Hainan Province in 2022], Department of Ecology and Environment of Hainan Province, June 2, 2023, https://hnsthb.hainan.gov.cn/xxgk/0200/0202/hjzl/hjzkgb/202306/t20230602_3428656.html.

4 World Health Organization, "WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide, And Carbon Monoxide," September 22, 2021, https://www.who.int/publications/i/item/9789240034228.

5 Hongyang Cui and Hui He, *Hainan's Clean Energy Vehicle Development Plan* (2019–2030) (International Council on Clean Transportation, 2019), https://theicct.org/publication/hainans-clean-energy-vehicle-development-plan-2019-2030/.

6 NEVs include battery electric vehicles, plug-in hybrid electric vehicles, and fuel cell electric vehicles, while natural gas-powered vehicles include compressed natural gas vehicles and liquefied natural gas vehicles.

7 Changchun Shao, 海南印发新能源汽车推广中长期行动方案 [Hainan publishes Mid- to Long-term Action Plan on New Energy Vehicle Deployment], Hainan Daily, August 9, 2023, http://hq.news.cn/20230809/6e473834f1054d53a3befd6830d76564/c.html.

8 Hongyang Cui, Yihao Xie, and Tianlin Niu, *Accelerating Hainan's Transition to New Energy Vehicles to Hit Its Target for Peak CO_2 Emissions by 2030* (International Council on Clean Transportation, 2022), https://theicct.org/publication/china-vehicles-accelerating-hainan-nev-transition-sep22/.

9 "Xi Focus: Xi announces China aims to achieve carbon neutrality before 2060," *Xinhau Net*, September 23, 2020, http://www.xinhuanet.com/english/2020-09/23/c_139388764.htm.

is mapped geospatially at a resolution of 0.25° × 0.25° of longitude and latitude.[10] We use the MEIC data to understand how much pollution is contributed by Hainan's transportation sector and where. The latest MEIC inventory is for 2020, while the baseline year in our Hainan vehicle emission inventory study is 2021; we adjusted the background emission inventory to align with the 2021 baseline year.

The emission inventory represents the direct or primary pollutants emitted from each source. The pollutants include carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds (VOCs), sulfur dioxide (SO_2), and ammonia (NH_3). These emissions are then subjected to complex atmospheric processes, during which they interact with other substances, undergo chemical reactions, and finally diffuse in the air to become air pollution, including ozone. To simulate the chemical reactions and diffusions of the emissions in the inventory, and thus project air quality, we apply the Weather Research and Forecasting (WRF) model and the Community Multiscale Air Quality (CMAQ) model. Both models are well-documented and widely used in air quality studies.[11]

Trinity Consultants conducted three key tasks for this study. First, they developed a projected background emission inventory for each sector in Hainan from 2021 to 2035, based on the 2020 MEIC data and a 2023 local emissions inventory projection study by Zhongjun Xu et al.[12] Trinity Consultants mapped the projected background emission inventory onto Hainan's geography in a grid of 3 km squares.

Secondly, based on the 2022 ICCT study, we used ICCT's Roadmap model to calculate and project pollutant emissions from Hainan's on-road transportation sector from 2021 to 2035 under both a Business-As-Usual (BAU) scenario and an Accelerated Electrification (AE) scenario.[13] Trinity Consultants applied the difference in emissions under the two scenarios for on-road transportation to the background emissions inventory map for 2021 to 2035. This gave us the background emission inventory under the AE scenario.

Lastly, Trinity Consultants conducted air quality modeling, using the WRF-CMAQ model, to convert the pollutant emission inventory (in grams per year) into air pollution (in $\mu g/m^3$). To measure ambient or outdoor air pollution, this study assesses the concentrations of nitrogen dioxide (NO_2), fine particulate matter ($PM_{2.5}$), and ozone. Ozone assessments include both a daily maximum 8-hour average concentration ($O_{3\text{-8h-max}}$) and an annual figure, based on the 90th percentile of the 8-hour average ($O_{3\text{-8h-max-90th}}$), meaning that the concentration is higher than this number 10% of the time.[14]

10 Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC), Department of Earth System Science Tsinghua University, accessed April 26, 2024, http://meicmodel.org.cn ; Bo Zheng et al., "Trends in China's Anthropogenic Emissions since 2010 as the Consequence of Clean Air Actions," *Atmospheric Chemistry and Physics* 18, no. 19 (2018): 14095–14111, https://doi.org/10.5194/acp-18-14095-2018; Meng Li et al., "Anthropogenic Emission Inventories in China: A Review," *National Science Review* 4, no. 6 (November 2017): 834–866, https://doi.org/10.1093/nsr/nwx150.

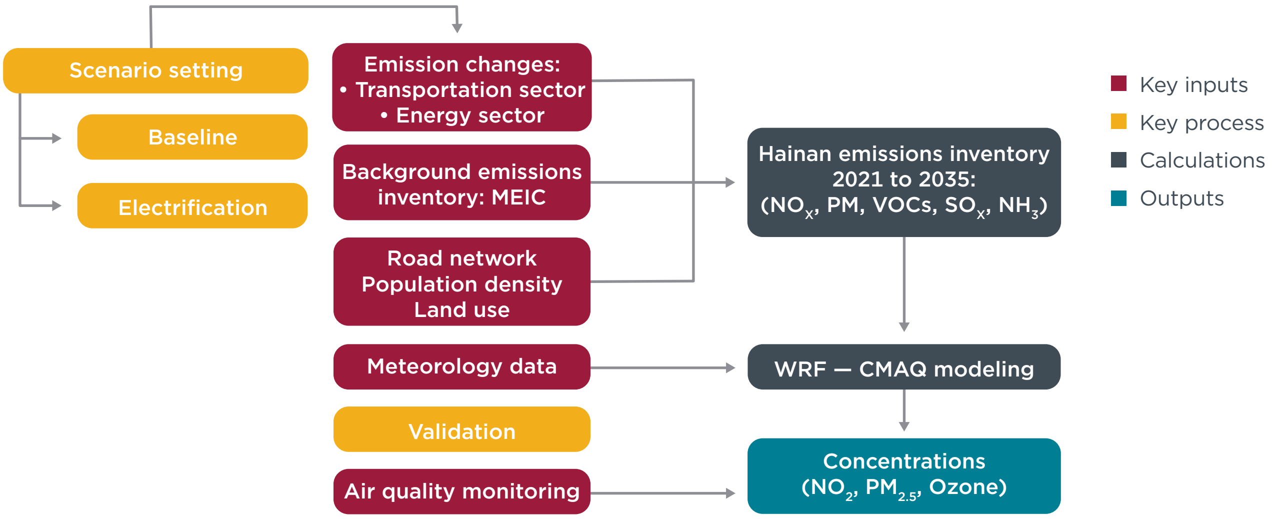
11 William C. Skamarock et al., *A Description of the Advanced Research WRF Version 4* (No. NCAR/TN-556+STR), 2019, https://doi.org/10.5065/1dfh-6p97; United States Environmental Protection Agency, CMAQ (Software, Version 5.0.2), 2014, available from https://doi.org/10.5281/zenodo.1079898.

12 Zhongjun Xu et al., "Air Quality Improvement through Vehicle Electrification in Hainan Province, China," *Chemosphere* 316 (March 2023): 137814, https://doi.org/10.1016/j.chemosphere.2023.137814.

13 International Council on Clean Transportation, Roadmap Model: ICCT Roadmap Model v2.2.0 Documentation, August 9, 2023, https://theicct.github.io/roadmap-doc/versions/v2.2/; Cui, Xie, and Niu, *Accelerating Hainan's Transition.*

14 GB 3095-2012, [Ambient air quality standard], https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/dqhjbh/dqhjzlbz/201203/W020120410330232398521.pdf; HJ 663-2013, [Technical regulation for ambient air quality assessment (on trial)], https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201309/W020131105548549111863.pdf.

Figure 1
Study methodology



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POLICY SCENARIOS

The two policy scenarios introduced in our 2022 Hainan vehicle emission inventory study are used, which for this working paper we refer to as the Business-As-Usual (BAU) and Accelerated Electrification (AE) scenarios. Table 1 is a summary of the vehicle categories in our analysis, the share of NEVs in all new vehicle sales in 2021 (as the baseline), and in the BAU and AE scenarios in 2025, 2030, and 2035.[15]

Table 1
NEV sales share in baseline year and assumptions for BAU and AE scenarios

Vehicle category			Baseline	Business-As-Usual			Accelerated Electrification		
			2021	2025	2030	2035	2025	2030	2035
Passenger vehicles	Private cars		26%	80%	100%	100%	80%	100%	100%
	Government vehicles		84%	100%	100%	100%	100%	100%	100%
	Taxis		96%	96%	96%	96%	100%	100%	100%
	Ride-hailing vehicles		100%	100%	100%	100%	100%	100%	100%
	Rental cars		100%	100%	100%	100%	100%	100%	100%
Buses			100%	100%	100%	100%	100%	100%	100%
Coaches	Tour coaches		37%	37%	37%	37%	70%	100%	100%
	Intercity coaches		18%	18%	18%	18%	25%	40%	60%
Trucks	Sanitation trucks		36%	50%	50%	50%	100%	100%	100%
	Light-duty trucks		14%	14%	14%	14%	50%	100%	100%
	Heavy-duty trucks	Yard trucks	0%	0%	0%	0%	100%	100%	100%
		Distribution trucks	3%	3%	3%	3%	20%	40%	60%
		Work trucks	0.4%	0.4%	0.4%	0.4%	15%	30%	45%

Source: Hongyang Cui, Yihao Xie, and Tianlin Niu, *Accelerating Hainan's Transition to New Energy Vehicles to Hit Its Target for Peak CO_2 Emissions by 2030* (International Council on Clean Transportation, 2022), https://theicct.org/publication/china-vehicles-accelerating-hainan-nev-transition-sep22/.

15 Cui, Xie, and Niu, Accelerating Hainan's Transition.

Vehicles are divided into a total of 13 vehicle categories and subcategories. Our classification of passenger vehicles, buses, and coaches is identical to Hainan's 2019 Development Plan. We refined the classification of trucks by creating five subcategories that reflect local fleet characteristics and highlight the diversity of truck specifications, operations, and modes of ownership. Our baseline is the share of NEVs in new vehicle sales in 2021.

The BAU scenario assumes NEV adoption consistent with empirical market trends in 2021. Under this scenario, we assume passenger vehicles and buses achieve the NEV sales share targets proposed in the 2019 Development Plan; meanwhile, we hold NEV sales of coaches and trucks constant, as the 2019 Development Plan did not specify targets for these vehicles.

The Accelerated Electrification (AE) scenario captures the full benefits of accelerating the uptake of NEV coaches and trucks. The NEV share of all new vehicle sales, which represents the pace of transition, was determined based on multiple factors: the most recent research on the availability and cost-effectiveness of NEV models in China; regulations and targets for coach and truck electrification in leading markets like California; and qualitative assessments with local stakeholders.

We recognize that these assumptions are static and may be conservative because Hainan is continuing to deploy battery electric coaches and trucks. However, we believe it is still a realistic representation of market trends absent the development of policies that differ significantly from the 2019 Development Plan.

EMISSIONS INVENTORY

BACKGROUND EMISSIONS INVENTORY

Table 2 shows the projected background emissions inventory under the BAU scenario of Hainan province for 2021, 2030, and 2035. As noted above, the projection is based on the 2020 MEIC background emission inventory and the total projected change in emissions as aligned with the study by Zhongjun Xu et al.[16] This study specifically considered that Hainan would experience rapid socioeconomic, industrial activity, and vehicle stock growth; the authors used the Monte Carlo simulation method to predict future emissions. The results of our transportation emission inventory will be sensitive to the choice of this background emission inventory. For example, under the BAU scenario, the high share of natural gas vehicles (especially for trucks) would lead to an increase in CO and VOC emissions.

16 Xu et al., "Air Quality Improvement through Vehicle Electrification."

Table 2
Hainan background emissions inventory under the BAU scenario

Hainan 2021 emissions (kt)							
Sector	SO_2	NO_x	CO	VOCs	NH_3	PM_{10}	$PM_{2.5}$
Industry and power	5.4	6.2	17.8	16.2	0.6	2.9	1.7
Residential	0.01	6.1	305.6	34.3	3.0	21.2	21.2
Agriculture	—	—	—	—	55.6	—	—
Transportation	0.04	18.6	21.7	2.5	0.004	0.5	0.5

Hainan 2030 emissions (kt)							
Sector	SO_2	NO_x	CO	VOCs	NH_3	PM_{10}	$PM_{2.5}$
Industry and power	17.7	20.0	57.7	52.6	1.9	9.3	5.6
Residential	0.01	6.0	302.2	33.9	3.0	20.9	20.9
Agriculture	—	—	—	—	55.6	—	—
Transportation	0.03	7.8	25.7	3.5	0.002	0.1	0.1

Hainan 2035 emissions (kt)							
Sector	SO_2	NO_x	CO	VOCs	NH_3	PM_{10}	$PM_{2.5}$
Industry and power	20.0	22.6	65.1	59.3	2.1	10.5	6.3
Residential	0.01	5.9	298.7	33.5	3.0	20.7	20.7
Agriculture	—	—	—	—	55.6	—	—
Transportation	0.03	6.5	34.1	4.9	0.001	0.1	0.1

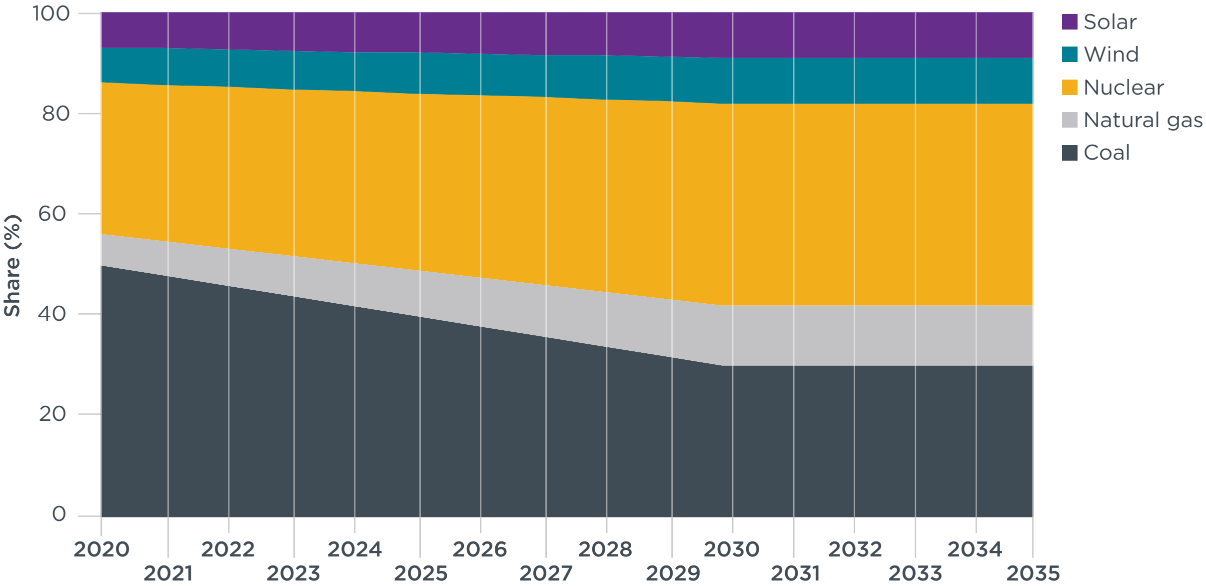
Under the AE scenario, the emissions from the residential and agriculture sectors will be unchanged from the BAU scenario. However, changes in emissions will occur in the transportation and power sectors because of increased electrification (see Figure 3).

ENERGY STRUCTURE

The mix of energy sources in the Hainan electricity grid from 2020 to 2035 (Figure 2) is based on the local plans and regulations included in ICCT's 2021 benchmarking study on pollution from on-road transport in Hainan.[17] The same grid mix is applied to the BAU and AE scenarios estimate the well-to-tank emissions of the transportation sector.

17 Hongyang Cui et al., *Policy Recommendations to Reduce Pollution from Hainan's On-Road Vehicle Fleet: Benchmarking with International Best Practices* (International Council on Clean Transportation, 2021), https://theicct.org/publication/policy-recommendations-to-reduce-pollution-from-hainans-on-road-vehicle-fleet-benchmarking-with-international-best-practices/.

Figure 2
Assumptions on the mix of energy sources powering the Hainan electricity grid from 2020 to 2035



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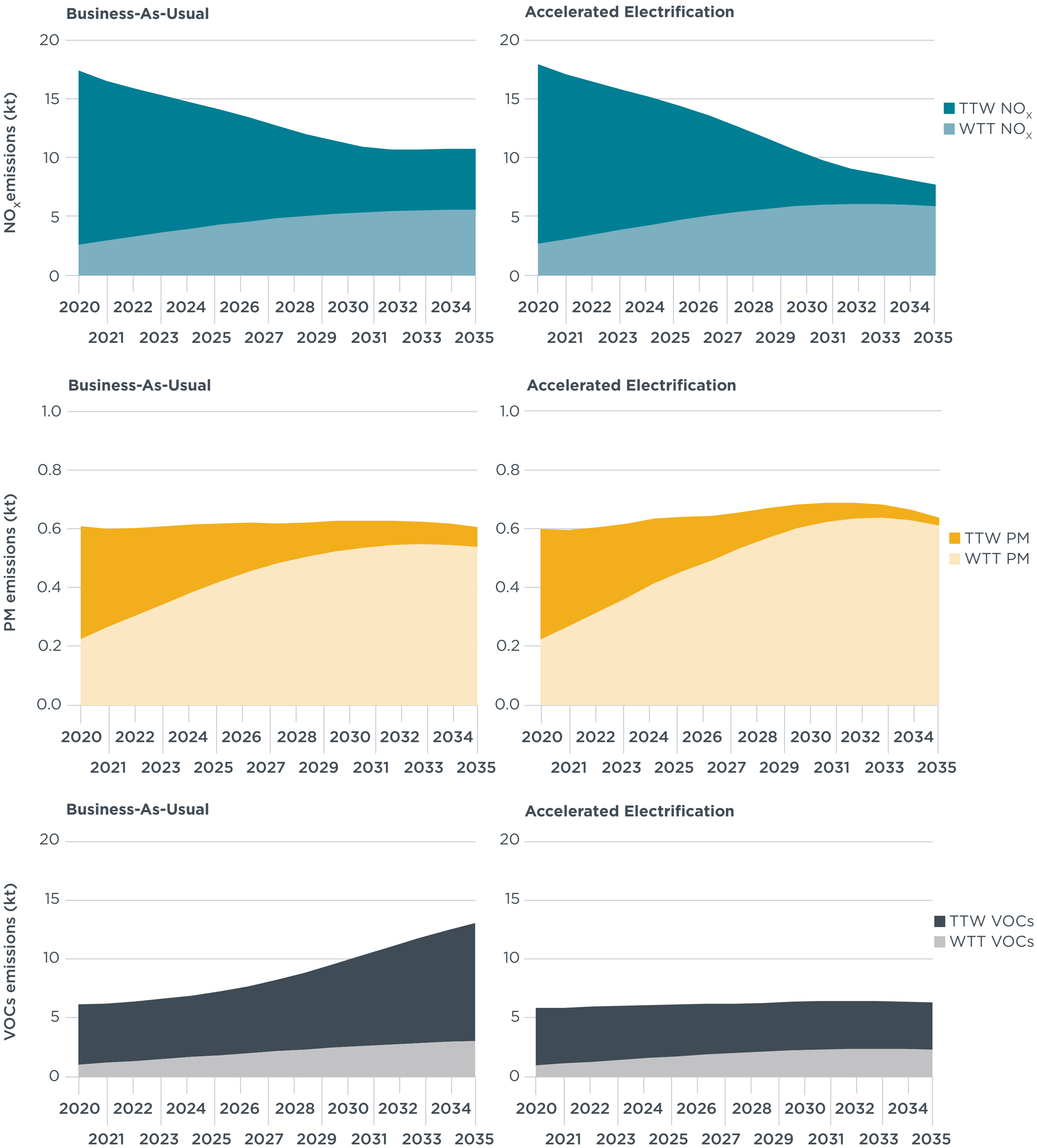
WELL-TO-WHEEL EMISSIONS OF THE TRANSPORTATION SECTOR

We used ICCT's Roadmap model to project both well-to-tank (WTT) and tank-to-wheel (TTW) emissions. Well-to-tank emissions are those generated during fuel production and transport before it is used in a vehicle. Tank-to-wheel emissions are generated during the use of that fuel by a vehicle. The results for NO_x, PM, and VOCs under the BAU and AE scenarios are shown in Figure 3. With accelerated electrification, tank-to-wheel emissions of NO_x, PM, and VOCs can be reduced by 70%, 65%, and 60%, respectively, in 2035. The well-to-tank NO_x and VOC emissions will decline by 2% and 24%, respectively, in the AE scenario in 2035, but PM will increase. That's because power plants are still using a high percentage of coal and natural gas, as shown in Figure 2. A faster phase-down of coal would benefit air quality directly and increase the benefits of vehicle electrification, especially for PM.

Figure 3

Well-to-tank (WTT) and tank-to-wheel (TTW) emissions under the two scenarios



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To determine how the AE scenario will impact Hainan's overall emission inventory, we first determine the difference in emissions between the BAU scenario and the AE scenario. These differences in emissions are then added to or subtracted from the background emissions inventory (shown in Table 2) in accordance with information about the road network, population density, land use, and specific points of interest (POIs) such as power plants. Differences in WTT emissions are applied to the industry sector, and differences in TTW emissions are applied to the transportation sector.

MODELING RESULTS AND DISCUSSION

MODELING RESULTS AND VALIDATION

The modeling results for all of Hainan province are presented in Table 3, along with the results for three cities: Haikou, the capital; Danzhou, which has a high amount of industrial activity; and Sanya, a popular tourist destination. The simulated annual average concentrations were determined using the above-mentioned weather (WRF) and air quality (CMAQ) models. For Hainan in the 2021 baseline year, the concentration of NO_2 was 5.0 µg/m^3, $PM_{2.5}$ was 11.6 µg/m^3, and ozone was 120.6 µg/m^3. Under the BAU scenario, changes to the NO_2, $PM_{2.5}$, and ozone concentrations in 2030 and 2035 are projected to be minimal, with some slight increases. In contrast, under the AE scenario, NO_2, $PM_{2.5}$, and ozone concentrations are projected to decline in 2030 and 2035 due to the electrification of buses and trucks.

Table 3
Modeling results for pollutants by area, scenario, and year

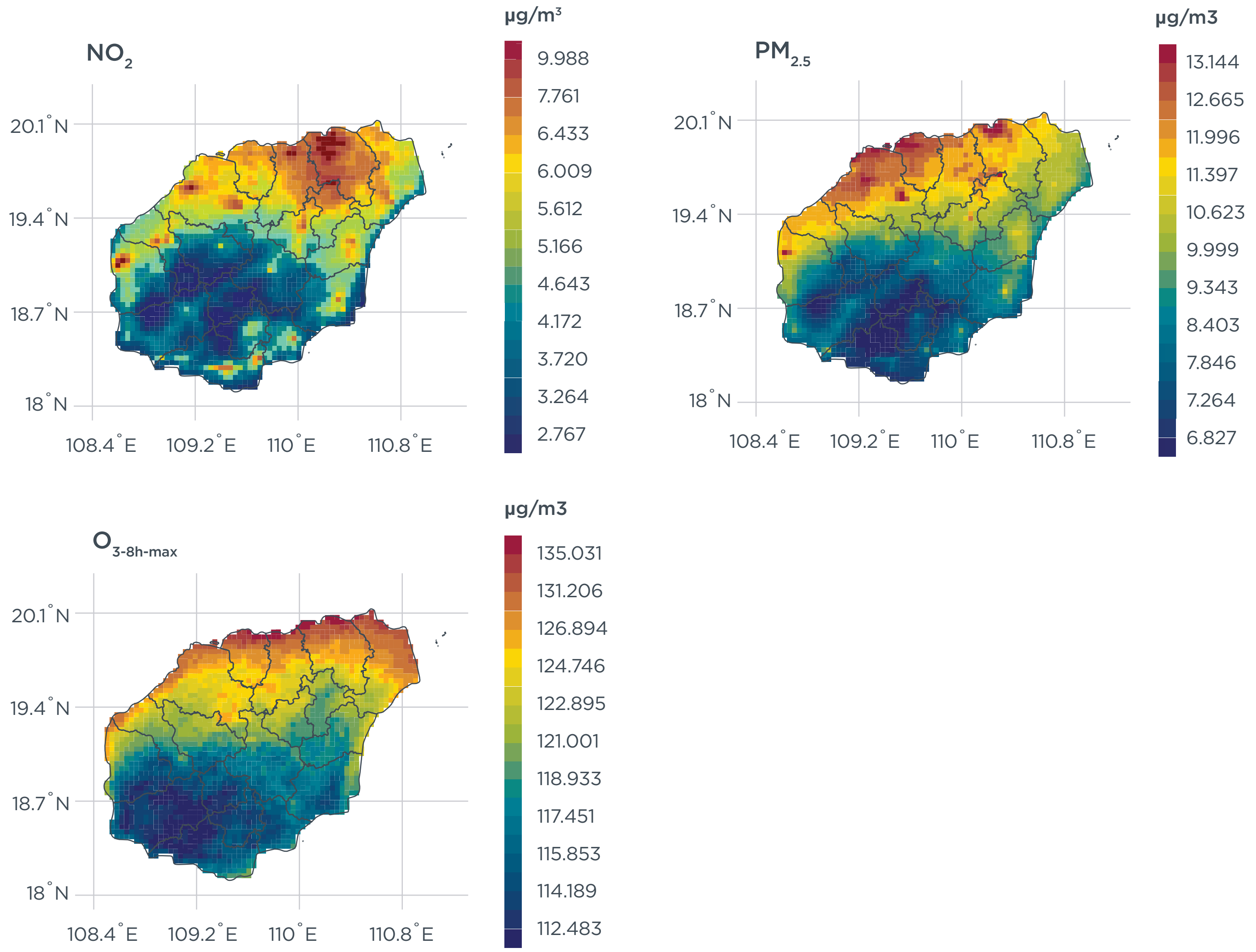
Area	Pollution	Scenario	Average concentration (µg/m^3)		
			2021	2030	2035
Hainan	NO_2	BAU	5.0	5.0	5.0
		AE		4.8	4.7
	$PM_{2.5}$	BAU	11.6	11.7	11.7
		AE		11.6	11.5
	Ozone	BAU	120.6	120.6	120.7
		AE		117.0	115.5
Haikou	NO_2	BAU	10.1	10.5	10.6
		AE		10.1	9.9
	$PM_{2.5}$	BAU	13.2	13.3	13.4
		AE		13.2	13.2
	Ozone	BAU	133.3	133.1	133.1
		AE		129.1	127.4
Danzhou	NO_2	BAU	8.4	8.7	8.8
		AE		8.4	8.3
	$PM_{2.5}$	BAU	13.2	13.3	13.3
		AE		13.2	13.2
	Ozone	BAU	124.8	124.7	124.7
		AE		121.0	119.3
Sanya	NO_2	BAU	5.5	5.6	5.6
		AE		5.4	5.2
	$PM_{2.5}$	BAU	7.6	7.7	7.7
		AE		7.6	7.5
	Ozone	BAU	115.3	115.2	115.2
		AE		111.8	110.3

Generally, northern Hainan has higher levels of air pollution than the south, likely because of its closer proximity to sources of transboundary emissions from neighboring

Chinese provinces and Southeast Asian countries. The highest concentrations of NO_2 and ozone are all in the Haikou urban area, and the highest $PM_{2.5}$ concentration is in the industrial city of Danzhou.

The geospatial distributions of 2021 baseline emissions are shown in Figure 4.

Figure 4
2021 baseline concentration maps for NO_2, $PM_{2.5}$, and ozone



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To validate the modeling results, we use 2021 environmental monitoring data from three national monitoring stations in Hainan Province. These are the Longhua Road Environmental Protection Bureau Dormitory station in Haikou City, the Hedongzi station in Sanya City, and the First High School station in Danzhou City. The detailed validation is listed in Appendix B.

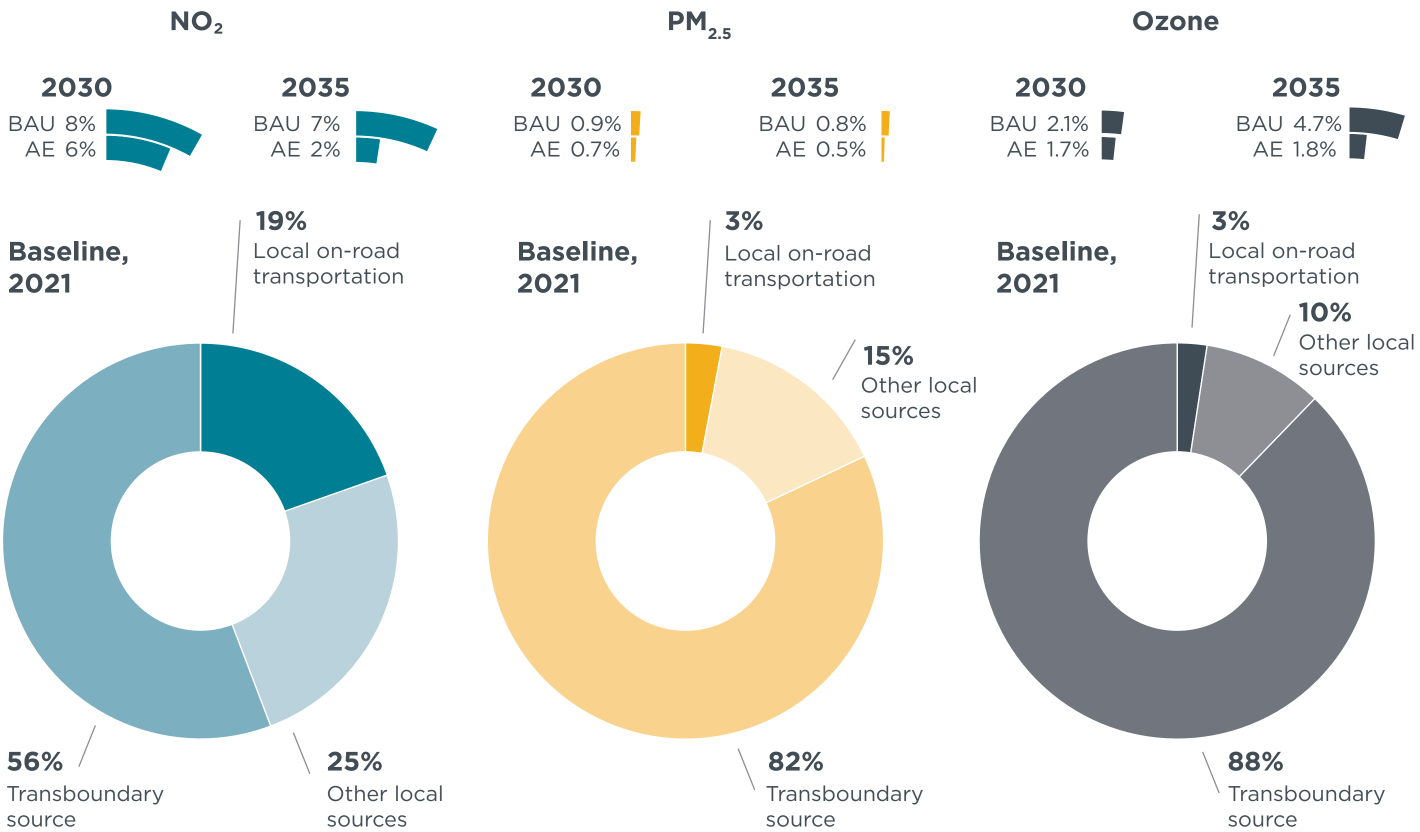
SOURCE APPORTIONMENT

In addition to the total concentrations of NO_2, $PM_{2.5}$, and ozone, we also simulate the pollution concentrations sourced from Hainan on-road transportation, other Hainan sectors (including residential, agriculture, industry, and power), and non-Hainan emissions for a source-apportionment analysis. The source-apportionment results for NO_2, $PM_{2.5}$, and ozone in Figure 5 indicate that most pollution comes from transboundary sources, which include emissions from other provinces of China or nearby countries. In 2021, transboundary sources contributed 56% of the NO_2, 82% of the $PM_{2.5}$, and 88% of ozone concentrations. This also helps explain why northern Hainan has a much higher concentration of pollutants than the south (Figure 4), as the northern part of the province is much closer to the transboundary sources. These transboundary sources are outside the control of the government of Hainan and its policies.

In 2021, local on-road transportation contributed to 20% (1.0 µg/m³) of the total NO_2 concentration from all sources, 3% (0.3 µg/m³) of the $PM_{2.5}$, and 2% (3.0 of µg/m³) of the ozone. Without accelerated electrification, the share of ozone contributed by local transportation is projected to grow from 2% in 2021 to 4.7% (5.7 µg/m³) in 2035. Accelerated electrification will reduce the transportation share of ozone to 1.8% (2.0 µg/m³). If transboundary sources of pollution are excluded, the share of local pollutants related to on-road transportation is much higher: 44% for NO_2, 18% for $PM_{2.5}$, and 12% for ozone. Still, increased electrification can reduce the share of pollution contributed by on-road transportation significantly.

Figure 5

Sources of pollutants in 2021 and share of pollutants from local on-road transportation only in 2030 and 2035 under the Business-As-Usual and Accelerated Electrification scenarios



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AIR QUALITY BENEFITS FROM ACCELERATED ELECTRIFICATION

Figure 6 below summarizes the reduction in pollution attributable to on-road transport with accelerated electrification, as compared with the BAU scenario in 2030 and 2035. The results prove that accelerated electrification of the on-road transport sector, especially for HDV fleets, will reduce NO_2, $PM_{2.5}$, and ozone, thereby contributing to air quality improvement. For air pollution sourced from on-road transportation only, the electrification of coaches and trucks can bring a 26%, 27%, and 24% respective reduction in NO_2, $PM_{2.5}$, and ozone concentrations in 2030 at the provincial level; and a 67%, 42%, and 63% reduction of these pollutants in 2035. Similar benefits can also be found in the cities of Haikou, Danzhou, and Sanya.

Figure 6

Reduction in pollutants from on-road transportation sources under the Accelerated Electrification scenario compared with the Business-As-Usual scenario in 2030 and 2035

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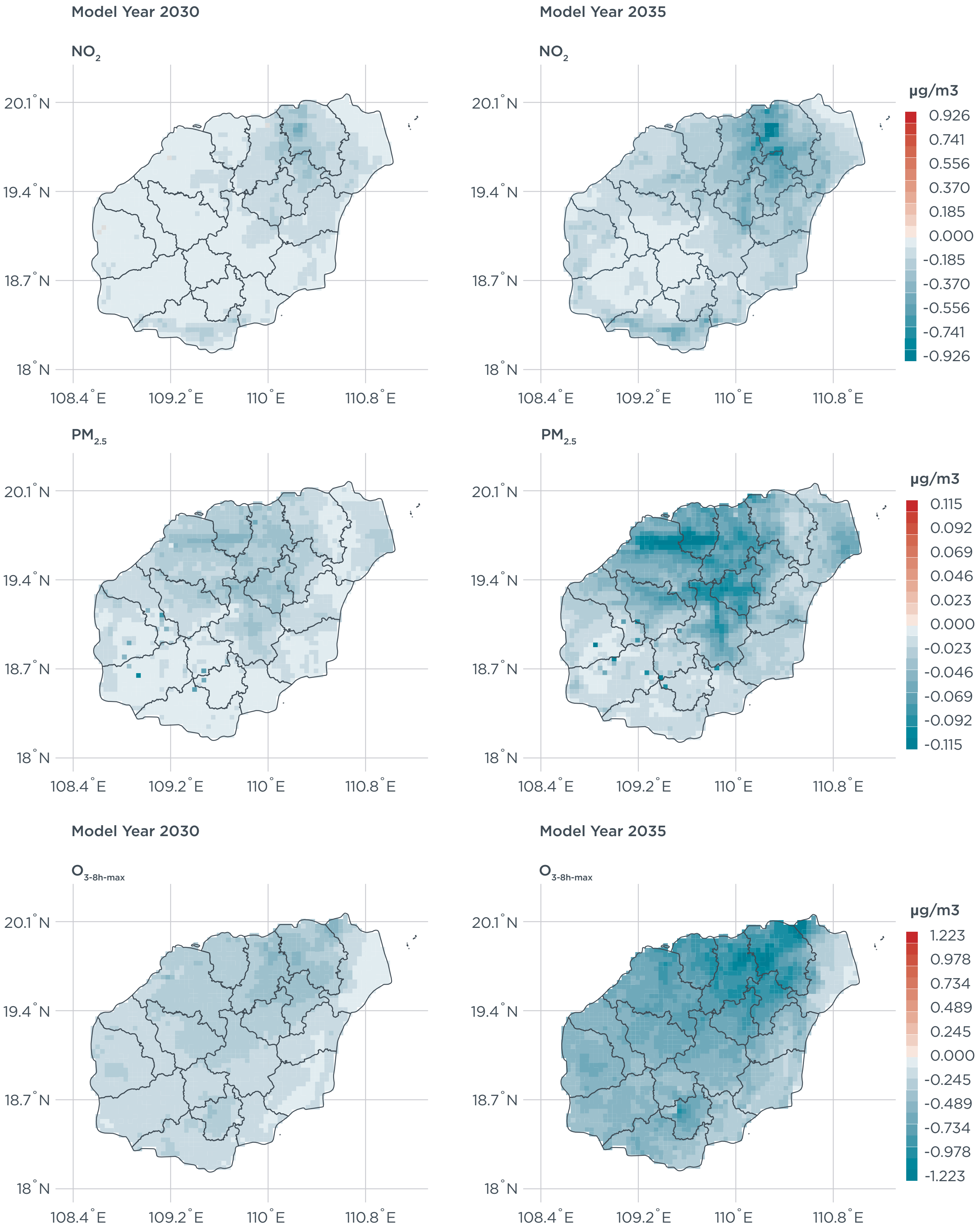
Additional concentration-reduction benefits are summarized in Figure 7. The concentration map, with 1-km grids, indicates that the largest improvement in NO_2, $PM_{2.5}$, and ozone concentrations in 2035 are in Haikou (0.6 µg/m^3 NO_2 reduction), Danzhou (0.6µg/m^3 $PM_{2.5}$ reduction), Haikou (5.0 µg/m^3 ozone reduction).

Figure 7

Reductions in daily concentrations of NO_2, $PM_{2.5}$, and ozone under the Accelerated Electrification scenario compared with the Business-As-Usual scenario in 2030 and 2035



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CONCLUSION

Air quality monitoring shows that transportation sources contributed to 20% (1.0 µg/m^3) of the total NO_2 concentration from all sources in Hainan in 2021, along with 3% (0.3 µg/m^3) of the $PM_{2.5}$, and 2% of the ozone (3.0 of µg/m^3). If we exclude transboundary sources, the share of local pollutants resulting from on-road transportation is much higher: 44% for NO_2, 18% for $PM_{2.5}$, and 12% for ozone.

Faster adoption of battery-electric coaches and trucks, as depicted in the AE scenario, could reduce pollution concentrations in Hainan attributable to road transport in 2030 by 26% for NO_2, 27% for $PM_{2.5}$, and 30% for ozone compared with the BAU scenario. In 2035, the AE scenario could reduce these road-transport-related concentrations by 67% for NO_2, 42% for $PM_{2.5}$, and 44% for ozone. Accelerated electrification will reduce the share of ozone attributable to on-road transportation from 2% in 2021 to 1.8% in 2035. In 2035, the ozone concentration related to on-road transport will be 3.0 µg/m^3 under the AE scenario, as compared with 5.7 µg/m^3 under BAE.

We estimate that accelerating the electrification of Hainan's coaches and trucks will help improve ambient air quality, especially for ozone, even as the province experiences higher levels of socioeconomic activity and growth in the number of vehicles. As Hainan has already made steady progress transitioning to electric passenger vehicles and urban buses, a renewed focus could be placed on electrifying trucks and other segments not covered in the 2019 Clean Energy Vehicle Development Plan. The Mid- to Long-term Action Plan on New Energy Vehicle Deployment (2023–2030) is a step in the right direction, while even more progressive targets — aimed at ensuring 100% truck electrification — can secure additional air quality benefits.

In this study, both the BAU and AE scenarios use the same assumptions about the power grid, projecting an increase in the share of nonfossil fuel electricity generation from 2020 to 2035. By 2035, coal-fired power plants will still represent about 25% of power generation. This assumption reflects policies and plans Hainan has adopted or announced. Greater air quality benefits from transportation electrification can be expected if Hainan were to shift power generation to renewables at a quicker pace.

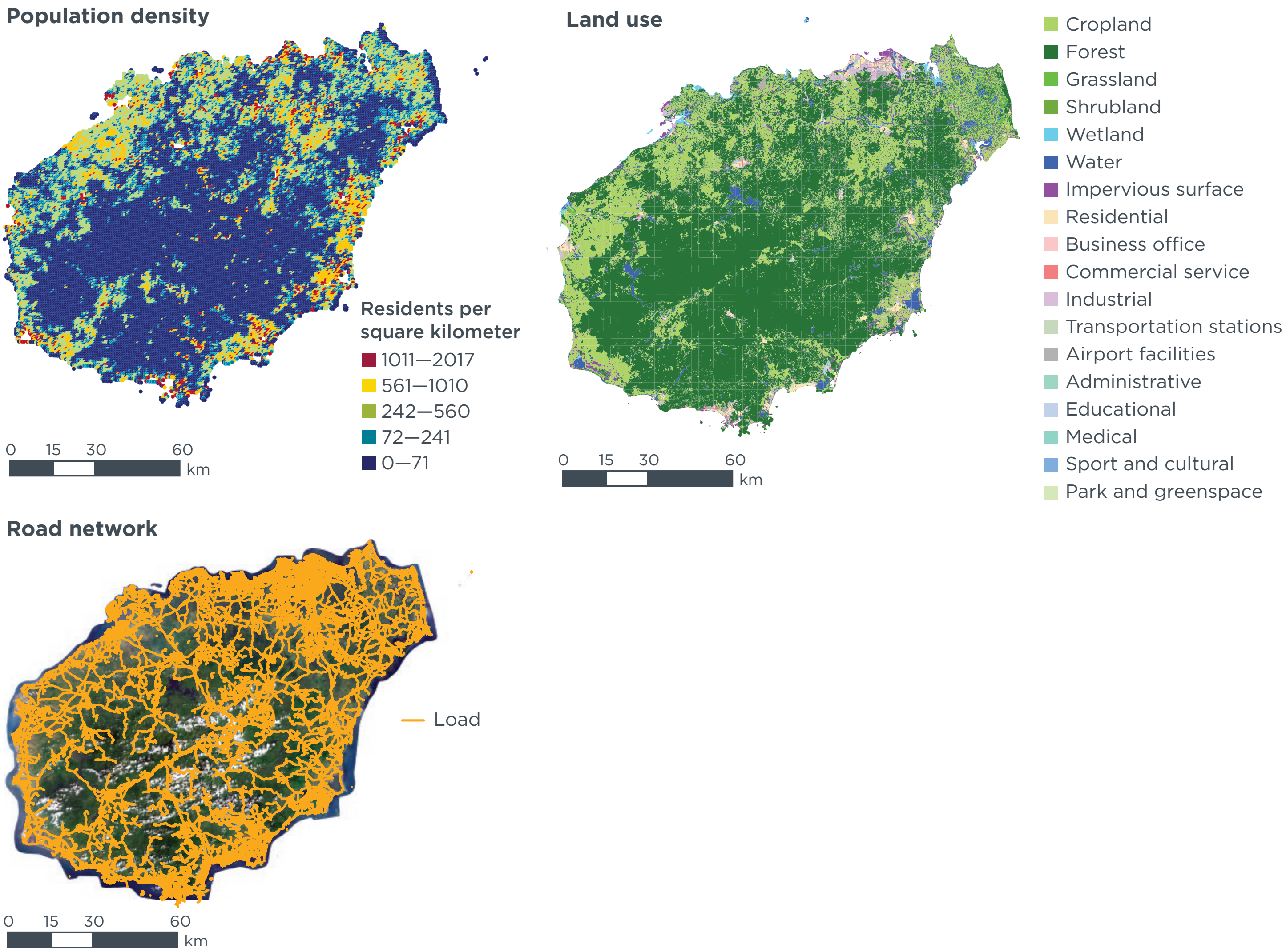
Finally, while on-road transportation is an important contributor to local air pollution, the source-apportionment results also demonstrate that transboundary sources are the dominating factor for pollution in Hainan. This suggests the importance of joint efforts toward an integrated air quality-control plan with neighboring Chinese provinces such as Guangdong and Guangxi to ensure that Hainan can meet its own air quality goals.

APPENDIX A

GEOGRAPHIC INFORMATION

Figure A1

Hainan province population density, land use, and road network



Sources: Xinliang Xu, 中国人口空间分布公里网格数据集 [China's population spatial distribution kilometer grid dataset], 2019, https://doi.org/10.12078/2017121101.

National Basic Geographic Information Center (China), Ministry of Natural Resources, *GlobeLand30* (dataset), accessed 2023, https://www.webmap.cn/commres.do?method=globeDetails&typ.

Xinliang Xu et al., 中国多时期土地利用遥感监测数据集 [China's multi-period land use remote sensing monitoring data set (CNLUCC)], Resource and Environment Science and Data Center, 2018, https://doi.org/10.12078/2018070201.

OpenStreetMap Contributors, Planet dump, accessed 2023, https://planet.osm.org.

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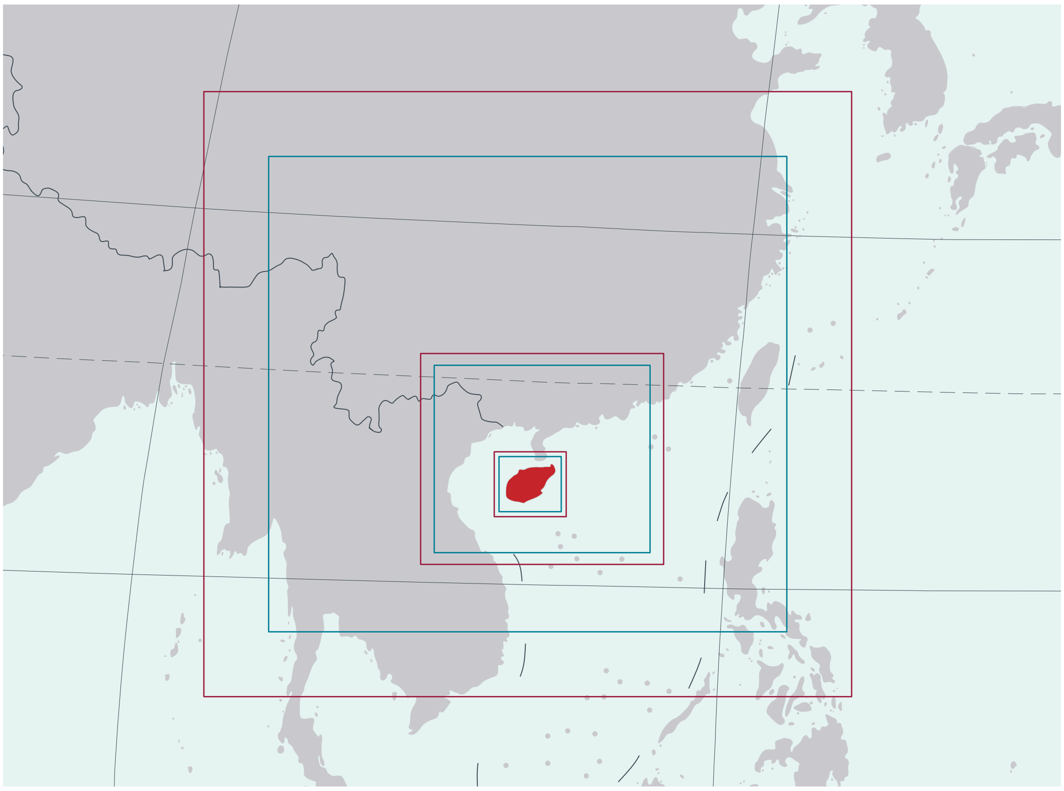
The modeling study domain is shown in Figure A2. The CMAQ modeling grid consists of three nested layers, where the outer layers provide boundary conditions for the inner layers to enhance the accuracy of the internal simulations. The first layer covers an area of 2,592 × 2,376 km with a horizontal resolution of 27 km. The second layer spans 1,080 × 936 km with a resolution of 9 km. The third layer encompasses the entire Hainan province within a range of 312 × 276 km, at a resolution of 3 km. To mitigate the impact of meteorological boundaries on the simulation results, the WRF model grid has at least six additional grid cells in all directions compared with CMAQ.

Figure A2
Modeling scope of meteorology and air quality



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APPENDIX B

We validate the modeling results with correlation coefficients, relative errors, mean fractional bias (B_{MF}) and mean fractional error (E_{MF}). According to literature reviews, the modeling results are in good ranges for B_{MF} (within ± 60%) and E_{MF} (< 75%).[18]

Table B1

Model validation

Pollutant	Sampling point	National control site (μg/m³)	Simulated concentration (μg/m³)	Correlation coefficient	Relative error(%)	BMF (%)	EMF (%)
NO_2	Haikou	10	10	0.48	5.32	-2.07	31.76
	Sanya	8	5	0.38	-37.60	-28.12	35.59
	Danzhou	10	8	0.41	-16.18	-13.42	30.74
$PM_{2.5}$	Haikou	14	14	0.68	-0.94	-15.14	41.38
	Sanya	12	8	0.61	-37.80	-41.87	51.58
	Danzhou	15	14	0.69	-9.42	-21.34	39.38
Ozone	Haikou	128	133	0.61	4.04	-3.93	19.01
	Sanya	106	116	0.72	9.53	2.11	16.10
	Danzhou	103	126	0.57	21.86	5.13	21.08

18 Guanghan Cao et al., "北京师范大学学报 (自然科学版) [Sourcing PM2.5 in cities in the Yangtze River Delta by CMAQ-ISAM]," *Journal of Beijing Normal University (Natural Science Edition)* 57, no. 6 (2021): 803–812, https://doi.org/10.12202/j.0476-0301.2021019; James W. Boylan and Armistead G. Russell, "PM and Light Extinction Model Performance Metrics, Goals, and Criteria for Three-Dimensional Air Quality Models," *Atmospheric Environment* 40, no. 26 (August 2006): 4946–4959, https://doi.org/10.1016/j.atmosenv.2005.09.087.

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