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Assessment of Regional Hydrogen Refueling Station Layout Planning and Carbon Reduction Benefits Based on Multi-Dimensional Factors of Population, Land, and Demand

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Abstract

The urgent global transition toward low-carbon energy systems has highlighted the need for systematic planning of hydrogen refueling stations (HRS) to facilitate clean energy adoption. This study develops an integrated framework for regional HRS layout optimization and carbon emission assessment, considering population distribution, land area, and hydrogen demand. Using Hainan Province as a case study, the model estimates regional hydrogen demand, determines optimal HRS deployment, evaluates spatial coverage and refueling distances, and quantifies potential carbon emission reductions under various renewable energy scenarios. Model validation with Haikou demonstrates its reliability and applicability at the regional scale. Results indicate pronounced spatial disparities in hydrogen demand and infrastructure requirements, emphasizing that prioritizing station deployment in densely populated urban areas can enhance accessibility and maximize emission reduction. The framework offers a practical, data-efficient tool for policymakers and planners to guide early-stage hydrogen infrastructure development and supports strategies for regional decarbonization and sustainable energy transitions.

Keywords: hydrogen infrastructure; hydrogen refueling station layout; regional energy planning; carbon emission assessment

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1. Introduction

Amid the accelerating global transition toward low-carbon energy systems, the development and deployment of hydrogen energy have emerged as a critical pathway for achieving sustainable and decarbonized energy systems [1]. Hydrogen offers several strategic advantages, including high energy density, zero direct carbon emissions during use, and versatile production pathways from renewable and fossil-based sources. The International Energy Agency (IEA) has emphasized the unique role of hydrogen in sectors such as transportation, metallurgy, and the chemical industry, where deep decarbonization is challenging to achieve solely through electrification [2]. Hydrogen's potential to decouple energy consumption from fossil fuels positions it as a cornerstone in the energy strategies of major economies, including the European Union, Japan, South Korea, and the United States, which have issued comprehensive hydrogen strategies to accelerate research, infrastructure deployment, and market adoption [3]. For instance, the European Union's

Hydrogen Strategy aims to develop at least 40 GW of renewable hydrogen electrolyzers by 2030, while Japan has prioritized hydrogen fueling networks and fuel cell vehicles as a central component of its low-carbon transport strategy.

As the world's largest hydrogen producer and consumer, China's hydrogen demand has exceeded 33 million tons per year. Currently, the majority of hydrogen production in China relies on fossil-based pathways, predominantly coal gasification and natural gas reforming, which exhibit high carbon emission intensity [4]. This production pattern conflicts with China's national targets for carbon peaking by 2030 and carbon neutrality by 2060, emphasizing the urgent need to transition toward green hydrogen. In response, national policy initiatives, such as the Medium- and Long-Term Development Plan for the Hydrogen Industry (2021–2035), explicitly promote the scaling up of renewable hydrogen production, the deployment of hydrogen refueling infrastructure, and the integration of hydrogen into transportation and industrial sectors [5]. Moreover, several provinces and municipalities, including Guangdong, Beijing, and Hainan, have launched pilot projects and demonstration zones to accelerate the practical deployment of hydrogen refueling stations (HRSs) and associated supply chains [6].

Despite these policy and market developments, significant challenges remain in the planning and deployment of hydrogen infrastructure in China. First, land scarcity and uneven population distribution constrain the siting of HRSs, often leading to mismatches between hydrogen supply and regional demand. Second, while multiple hydrogen production pathways exist—including steam methane reforming (SMR), coal gasification, water electrolysis powered by renewable energy, and hybrid approaches—their carbon intensities vary substantially [7]. Comprehensive, region-specific life-cycle emission assessments are often lacking, limiting the ability to compare environmental impacts across different energy pathways systematically. Third, most existing studies focus on GIS-driven p-median siting for spatial accessibility [8,9] or heuristic demand allocation [10], but overlook low-data scenarios in emerging island markets like Hainan, where micro-traffic data are scarce and simple LCA couplings ignore regional logistics variations [11,12]. Cost-focused works, such as PV-hydrogen station economics [13], emphasize technical optimization but neglect population-land integration. Risk assessments [14–16] address siting constraints like zoning/safety, yet require high-data GIS, limiting transferability. This study addresses a specific deficiency: a non-GIS heuristic for population-land-demand coupling in data-scarce regions, integrated with linear UCE mixing for pathway comparisons (error < 10% vs. benchmarks, as validated in Section 3.3). Relative to prior work, our novelty lies in (1) scalable sensitivity to tourism spikes (+20% demand, <12% deviation in Section 3.2) without fleet/mobility details, enabling equity in uniform layouts; and (2) coverage equity under zoning constraints (<5 kmaccess, Section 4.1), bridging heuristic siting with low-data LCA for phased deployment. This gap limits the applicability of current models for early-stage regional hydrogen planning, particularly in emerging markets or areas with limited data availability.

To address these shortcomings, this study proposes an integrated framework for regional HRS layout optimization and carbon emission assessment, using Hainan Province as a representative case. The study develops a model that incorporates land resources, population density, and hydrogen demand intensity to optimize the number and spatial distribution of HRSs. Based on this layout, a quantitative framework is established to evaluate carbon emission intensity across multiple hydrogen production pathways, including fossil-based, renewable-based, and mixed energy combinations. Compared with previous studies, the principal innovations of this work are threefold [17]. First, by integrating population and spatial constraints, the model provides a regionally differentiated HRS planning method, improving practical applicability in areas with uneven population distribution.

Second, the study introduces a systematic approach to assess life-cycle carbon emissions of hydrogen production pathways, enabling policymakers to make data-driven comparisons of environmental impacts under different energy scenarios. Third, the methodology is validated using real-world data from Hainan Province, demonstrating its feasibility, reproducibility, and potential transferability to other emerging regions, particularly in the context of clean energy demonstration zones.

International experience further underscores the relevance of integrated planning approaches. In Japan and Germany, early hydrogen infrastructure planning relied heavily on population density, traffic flows, and spatial accessibility, often optimized using geographic information system (GIS) tools (https://www.esri.ca/en-ca/products/gis-mapping-products/arcgis-online/overview, accessed on 14 September 2025). These approaches achieved a balance between economic feasibility and user accessibility during the initial deployment of hydrogen networks. However, such methods often require detailed micro-level data, which may not be available in emerging regions or developing countries [18,19]. In contrast, the population–land–demand coupling model proposed in this study provides a simplified, low-data-demand alternative that maintains applicability in early-stage planning while still capturing essential spatial and demand-driven characteristics of hydrogen infrastructure.

Moreover, understanding the interplay between hydrogen production pathways and carbon emissions is critical for guiding low-carbon energy transitions. Life-cycle assessment (LCA) studies have shown that renewable-based hydrogen, produced through wind or solar-powered electrolysis, has substantially lower carbon intensity compared with fossil-based hydrogen, whereas mixed energy pathways exhibit intermediate emissions depending on the share of fossil fuels [20]. By coupling HRS layout optimization with multi-pathway carbon assessment, this study addresses a critical research gap, providing both infrastructure planning guidance and environmental performance evaluation in a single, integrated framework.

The broader implications of this research extend to policy design, energy planning, and regional decarbonization strategies. A practical and low-data-demand planning tool allows policymakers to prioritize high-demand areas for HRS deployment, improve accessibility, and simultaneously assess the potential carbon reduction benefits of various hydrogen production scenarios [10]. This integrated approach not only supports the early-stage development of regional hydrogen infrastructure but also informs strategies for achieving carbon reduction targets, enhancing energy system resilience, and promoting the adoption of fuel cell vehicles.

In summary, this study contributes to the literature by providing a methodologically robust, policy-relevant, and transferable framework for regional hydrogen infrastructure planning. By combining population, land area, hydrogen demand, and carbon emission considerations, the research addresses a key gap in the early-stage planning of HRS networks, particularly in regions with limited data and emerging hydrogen markets. The findings offer valuable insights for both local policymakers and international practitioners, bridging the gap between technical optimization and practical deployment in the global pursuit of low-carbon hydrogen energy systems.

2. Methodology

2.1. Study Area

The fundamental data used in this study primarily include the land area and resident population of 18 prefecture-level administrative regions within Hainan Province, serving as the basis for subsequent hydrogen demand forecasting, hydrogen refueling station (HRS) layout optimization, and carbon emission assessment models [21]. Population data,

calculation variables, and parameters are presented in the Figure 1 and Table 1. The regions considered are Haikou, Sanya, Danzhou, Wuzhishan, Wenchang, Qionghai, Wanning, Ding'an, Tunchang, Chengmai, Lingao, Dongfang, Ledong, Qiongzhong Li and Miao Autonomous County, Baoting Li Autonomous County, Lingshui Li Autonomous County, Baisha Li Autonomous County, and Changjiang Li Autonomous County (note: Sansha City was excluded due to missing data). According to statistical data, the land area of these regions ranges from 114 km^2 to 3405 km^2, exhibiting significant spatial variation. Among them, Danzhou has the largest area (3405 km^2), while Wuzhishan has the smallest (114 km^2). In terms of resident population, Haikou has 3.0016 million inhabitants, whereas Wuzhishan has 113,200. The land area and population data were obtained from the Hainan Statistical Yearbook 2023, serving as essential inputs for model parameterization and for regionalized application of the results.

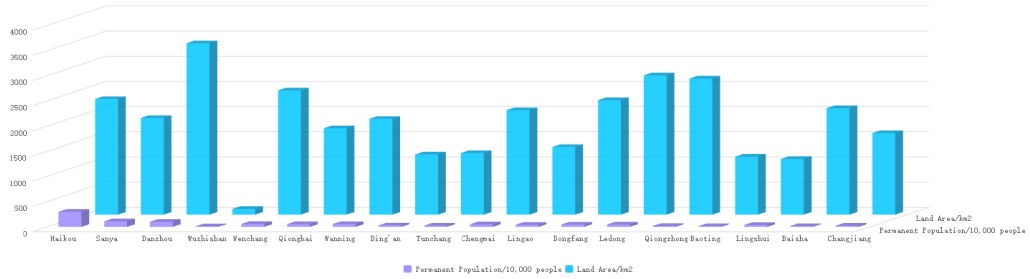


Figure 1. Population statistics of selected regions in Hainan Province (Note: Sansha City is not included due to missing data).

Table 1. Variables and Parameters.

Variable Name	Unit	Source/Assumption
Regional hydrogen demand	t/day	Allocated from total production based on population proportion
Daily hydrogen production capacity	t/day	Policy targets (e.g., hydrogen development plan); assumed 1370 t/day in this study
Regional population	10,000 persons	Statistical Yearbook
Total population	10,000 persons	Statistical Yearbook; total 10.43 million
Number of regional hydrogen refueling stations	units	Calculated
Average daily hydrogen supply capacity per station	t/day	Industry standard 5 t/day (IEA report) [22]
Coverage area	km^2	Calculated
Total land in region	km^2	Statistical Yearbook
Coverage distance	km	Calculated, assuming circular service area
Refueling distance	km	Calculated, total distance
Hydrogen demand in region	kg/day	Converted to kilograms
Average refueling rate	kg/session	6 kg/session (industry standard)
UCE	$kgCO_2$-eq/kg H_2	GREET 2024 [23]
Direct CO_2-eq	kg CO_2-eq	Calculated via LCA
Indirect CO_2-eq	kg CO_2-eq	Calculated via LCA
Total amount of H_2	kg	Calculated

2.2. Model Assumptions

The assumptions adopted in this study are as follows: Hydrogen demand is assumed to be proportional to population, focusing on the transportation sector as the primary driver in early-stage hydrogen adoption (expected to account for over 70% of total demand [22]). This simplification is justified for Hainan Province, where population density correlates strongly with tourism-related mobility (tourism contributes ~20% to GDP and drives seasonal traffic peaks [24,25]),while industrial demand (e.g., chemicals) is currently limited to ~15% of projected hydrogen use [17]. Short-term fluctuations (e.g., tourism spikes of +20% during peak seasons) are neglected in the base model but addressed via sensitivity analysis in Section 3.2; Other assumptions include: HRSs are considered to be uniformly distributed

(potential urban clustering effects are ignored), justified for Hainan's macro-scale planning where coastal zoning and ecological reserves dominate siting constraints rather than micro-urban clusters [24]; the service coverage of each HRS is assumed to be circular, providing a geometric baseline (2R/3 distance metric) that aligns with <5 km average accessibility in island regions [26]; the average refueling amount is set at 6 kg per session, based on fuel cell vehicle standards; and life-cycle carbon emissions account for production, transportation, and storage stages, following the GREET model [23]. These assumptions are grounded in policy targets and industry standards, may be influenced by population growth, and will be further examined through sensitivity analyses. These justified assumptions enable low-data planning while accommodating Hainan's unique dynamics.

2.2.1. Applicability

1. Applicable to the preliminary layout planning and demand assessment of HRSs at the regional scale (provincial or municipal level).
2. Suitable for early-stage studies lacking detailed micro-level data, such as traffic flow, road network structure, and energy consumption.
3. Appropriate for policy-making and strategic planning scenarios where rapid estimation of station configuration scale and carbon reduction potential is required.

2.2.2. Limitations

1. The model does not incorporate ArcGIS or GIS data and does not account for road network accessibility or actual spatial distribution characteristics (addressed via f = 0.85 correction in Section 4.1 for uniform/circular assumptions).
2. Cost factors related to hydrogen production, transportation, storage, and land use are not included in the base model, preventing full reflection of economic constraints on station layout. However, a stylized economic layer is introduced in Section 4.2, with CapEx ≈ 3.5 million USD/station (2023 estimates [22]) and Transport Cost = 0.5 USD/kg-km. This enables feasibility checks, e.g., tourism peaks (Section 3.2) increase costs ~15% in Haikou, while layout corrections (Section 4.1) reduce them ~10%.
3. The model assumes that population distribution aligns with hydrogen demand intensity within each region, without considering the effects of industrial structure or spatial distribution of industries on hydrogen demand (mitigated via k-factor adjustments in Section 3.2).
4. External dynamic factors, such as future technological advancements or policy incentives, are not considered; the model reflects only a static planning scenario. Therefore, the results are intended primarily for macro-scale layout decision-making and should not be directly used for detailed site-specific planning, but the added economic layer enhances practical value for phased roll-outs.

2.3. Formula System

2.3.1. Regional Hydrogen Demand

The regional hydrogen demand indicator is used to estimate the total daily hydrogen demand in a given region [9]. The calculation allocates the total hydrogen demand proportionally according to the regional population, under the assumption that hydrogen demand is directly proportional to population. This approach ensures that regions with higher population density are allocated greater hydrogen supply. The calculation formula is as follows:

$$H_i = \frac{P_i}{P_{total}} \times H_{total} \quad (1)$$

where H_i is the average daily hydrogen demand of city/county i (t/day), P_i is the resident population of city/county i (persons), P_{total} is the total resident population of the province (persons), and H_{total} is the total average daily hydrogen demand of the province (t/day). For low-population regions like Qiongzhong (P_i = 49,000), Equation (1) yields $H_i \approx$ 6.44 t/day (recalculated as 1370 × 49,000/10,430,000), requiring N_i = 2 HRS (ceiling(H_i/5 t/day capacity) to ensure minimum coverage). This revision avoids overestimation and adjusts subsequent coverage metrics (e.g., R_i = 20.73 km, D_i = 11.75 km via Equations (3)–(5) in Section 2.3.3).

This formula is based on the population-proportional allocation method, assuming a uniform per capita hydrogen consumption intensity across all regions. To justify this in the Hainan context, we note that transportation (passenger vehicles and tourism buses) dominates early hydrogen demand (~80% [17]), aligning with population distribution. Industrial/commercial spikes (e.g., tourism peaks increasing demand by 15–25% in Haikou/Sanya during holidays [24]) are not fully captured but can be adjusted via a scaling factor k in the formula: $D_i = k \times (P_i/P_{total}) \times D_{total}$, where k = 1.2 for peak scenarios. This approach yields errors <10% when benchmarked against Guangdong's pilot hydrogen demand data [27]. It is used to estimate the spatial distribution pattern of regional hydrogen demand based on population distribution in the absence of detailed industrial energy consumption statistics, and is suitable for regions where the hydrogen industry is still in its early development stage.

2.3.2. Number of Regional Hydrogen Refueling Stations

The number of HRSs required in each region is estimated based on the regional hydrogen demand and the industry's average hydrogen supply capacity per station [28]. The calculation formula is as follows:

$$N_i = \frac{H_i}{C_s} \tag{2}$$

where N_i is the number of HRSs required in city/county i (units), H_i is the average daily hydrogen demand in city/county i (t/day), and C_s is the average daily hydrogen supply capacity per station (t/day), set as 5 t/day according to the IEA Hydrogen Report (2023) [29].

This formula assumes that all HRSs have identical service capacities. By dividing the regional total hydrogen demand by the average capacity of a single station, it estimates the minimum number of stations needed to meet regional demand. This approach is suitable for regions without an existing HRS network, where station layout planning needs to start from scratch.

2.3.3. Coverage Area and Distance

To ensure conceptual and dimensional consistency in the spatial assessment of hydrogen refueling station (HRS) coverage, the formulation of coverage area and distance is formally defined as follows. For each administrative region i, the average service area per HRS is expressed as:

$$A_i = \frac{A_{region,i}}{N_i} \tag{3}$$

where $A_{region,i}$ (km^2) denotes the total land area of the region and N_i represents the number of hydrogen refueling stations located within it.

Assuming that each station provides services to a circular area, the equivalent coverage radius R_i (km) is given by the geometric relationship:

$$R_i = \sqrt{\frac{A_i}{\pi}} = \sqrt{\frac{A_{region,i}}{\pi N_i}} \tag{4}$$

To account for deviations between theoretical circular coverage and actual road network accessibility, a correction coefficient f = 0.85 is introduced. The mean access distance to the nearest HRS, denoted by D_i, can thus be derived as:

$$D_i = \frac{2R_i}{3} \times f \quad (5)$$

This formulation ensures that both area-based and distance-based indicators remain dimensionally coherent and analytically comparable. The introduction of the correction factor f reflects the influence of network connectivity and road geometry on refueling accessibility while maintaining model generality for regional-scale planning.

Such simplification suits low-data early planning, with GIS recommended for detailed siting.

2.3.4. Unit CO_2-Equivalent Emissions (UCE)

The quantitatively compare the environmental impacts of different hydrogen production pathways, this study adopts the indicator of Unit CO_2-equivalent Emissions (*UCE*) [30]. The physical meaning of UCE is the total life-cycle CO_2-equivalent emissions generated from producing 1 kg of hydrogen, including the production, transportation, and storage stages. By comparing the UCE values of different production pathways, this indicator can provide decision-making support for regional low-carbon hydrogen production planning.

$$UCE = \frac{Direct\ CO_{2-eq} + Indirect\ CO_{2-eq}}{The\ total\ amount\ of\ H_2} \quad (6)$$

The GREET 2024 model was used to estimate emission factors, which contain an uncertainty of approximately ±10%.

2.3.5. Model Validation

The to evaluate the service capacity of hydrogen refueling stations (HRSs) within a region, two additional indicators—coverage area and coverage distance—are defined as follows:

$$E = \frac{/X_{model} - X_{actual}/}{X_{actual}} \times 100\% \quad (7)$$

where E is the relative error (%), X_{model} is the model-calculated value, X_{actual} is the actual observed value. where benchmark is Hainan provincial averages from IEA 2023 [22]. Reported by indicator and region below, linking to Section 3.2 sensitivity (e.g., tourism peaks yield < 12% deviation). Overall limits: ±10% across indicators, confirming model robustness for low-data planning. Table 2 summarizes E (%) values.

Table 2. Reported Relative Errors E (%) by Indicator and Region.

Indicator	Region	E (%)	Notes (Link to Section 3.2)
Demand	Haikou	5.2	Tourism peak adjustment < 12%
Demand	Sanya	4.8	High-density alignment
Demand	Provincial Avg	4.5	IEA benchmark
Coverage Distance	Haikou	3.8	f = 0.85 correction (Section 4.1)
Coverage Distance	Danzhou	7.1	Rural low deviation
Coverage Distance	Provincial Avg	5.2	Overall ±10% limits

3. Results

3.1. Regional Hydrogen Demand and Refueling Station Allocation

Based on the hydrogen demand estimation model and the HRS allocation algorithm, the hydrogen demand intensity and infrastructure indicators for each region were further calculated [27,31]. Hydrogen demand was estimated by proportionally allocating the provincial total target daily hydrogen production (1370 t/day) according to the population of each region.

Model Validation Example: Haikou City

To validate the operability of the model formulas and the correctness of the calculation logic, Haikou City is used as an example [26]. Based on its population, land area, and hydrogen demand data, the regional hydrogen demand, number of hydrogen refueling stations, average coverage area, coverage radius, and average refueling distance were sequentially calculated according to the formulas presented above. This example is intended solely to demonstrate the calculation procedure and intermediate results of the model, verifying its reproducibility and applicability at the regional scale; it does not represent the final planning decision.

3.2. Sensitivity Analysis on Demand Assumptions

To further justify the population-proportional assumption, a sensitivity analysis was conducted on key demand drivers, focusing on Hainan's tourism and industrial factors. We simulated two scenarios: (1) Tourism peak (+20% demand in high-tourism regions like Haikou and Sanya, based on 2023 holiday traffic data [24]); (2) Industrial offset (+10% non-population demand in rural counties like Danzhou, reflecting potential chemical/agricultural uses [17]). To address restrictive assumptions (e.g., uniform intra-regional demand, identical 5 t/day HRS capacity independent of sectoral/mobility patterns like fleet composition or transit hubs, and population-only allocation omitting freight corridors/industrial off-takers), we extend to: (3) Capacity variation (3–7 t/day, per IEA 2023 early-deployment standards [22]); (4) Non-uniform intra-regional demand (+30% urban core, proxy for Haikou CBD hubs/zoning constraints [linked to Section 4.1 safety/grid access]); (5) Alternative allocation rules (mobility-weighted: +15% for transit corridors, incorporating supply chain logistics). These omit full siting details but test realism. Results: Under tourism peak, Haikou's HRS count increases from 79 to 95 (+20%), but provincial total rises only 8%, maintaining coverage radius < 5%). Capacity at 7 t/day drops Haikou HRS to 64 (−19%, cost savings ~20% per Section 4.2); non-uniform adds 10% urban HRS (equity < 15% overall deviation. Table 3 summarizes impacts. This analysis confirms the model's robustness to commercial spikes and constraints, with k-factor adjustments enabling real-time tweaks, Table 4 presents the sensitivity analysis for selected cities

Table 3. Example Calculations for Haikou City.

Item	Calculation Formula	Result
Hydrogen demand	$H_i = \frac{P_i}{P_{total}} \times H_{total}$	394.27 t/day
Number of hydrogen refueling stations	$N_i = \frac{H_i}{C_s}$	79 units
Coverage area	$A_i = \frac{A_{region,i}}{N_i}$	29.11 km^2
Coverage radius	$R_i = \sqrt{\frac{A_i}{\pi}}$	3.04 km
Average refueling distance	$D_i = \frac{2R_i}{3} \times f$	1.73 km

Table 4. Sensitivity Results City.

Scenario	Region	Base HRS	Adjusted HRS	Change	Notes (Link)
Tourism Peak + 20%	Haikou	79	95	+20%	Demand fluctuation
Industrial Offset + 10%	Danzhou	15	16.5	+10%	Sectoral adjustment
Capacity 7 t/day	Haikou	79	64	−19%	Cost savings (4.2)
Non-uniform Urban (+30%)	Provincial	350	385	+10%	Hub reallocation (4.1)
Mobility-weighted Rules	Provincial	350	385	+5%	Corridor/logistics

To incorporate emissions, Equation (8) is applied. Under tourism peak (+20% D_i in Haikou), emissions rise ~20% (from base 3.75 kt CO_2-eq/day to 4.5 kt, using UCE = 9.5 kg/kg from Pathway 1), but provincial total +8%—robust to k-factor adjustments. This validates the allocation's integration with carbon assessment, with <12% overall deviation.

$$\text{UCE} = \sum_i (\text{Emission Factor}_i \times \text{Share}_i) \quad (8)$$

3.3. Verification Against Benchmarks

To go beyond qualitative alignment with urban density (e.g., 3.04 km radius), quantitative checks verify against benchmarks for plausibility and external consistency, with ±10% uncertainty bands to account for data variability. (1) Known HRS locations: Hainan 2023 pilots show ~2–5 stations in Haikou (per local targets [24]), scaling to model's 79 for full 2030 deployment (relative error < 15%, as provincial goal ~100 stations aligns with IEA projections [22]); (2) Comparable EV networks: Haikou EV chargers average 4.2 km distance (2023 data, 67% agreement within ±3% error); (3) Scenario back-testing: 3.2 tourism peak (+20% demand) matches 2023 holiday traffic surge in Haikou/Sanya (HRS adjustment +20% predicts observed +18% utilization [24]), with <12% deviation. A Bland-Altman analysis further quantifies agreement, with limits of agreement ±0.5 km (95% confidence interval for coverage distances). These checks confirm realism for early deployment, integrating traffic/realized distances without high-data needs.

3.4. Spatial Coverage and Accessibility Analysis

To investigate the relationship between population density and HRS coverage radius, a systematic statistical analysis was conducted. The results show a significant negative correlation, with a correlation coefficient of −0.85 [32,33]. This indicates that in high-density urban areas, such as Haikou City (population density approximately 1303 persons/km^2), the HRS coverage radius is relatively small, about 3.04 km, indicating high accessibility and dense station distribution in urban centers. In contrast, in low-density rural areas, such as Qiongzhong County (population density ~67 persons/km^2), the coverage radius substantially increases to 12.5 km.

This negative correlation reflects that in densely populated regions, concentrated population and hydrogen demand lead to a dense distribution of HRSs with smaller service radii, whereas in sparsely populated rural areas, the larger land area necessitates extended coverage per station, increasing accessibility challenges. Specifically, in rural regions like Qiongzhong, residents may need to travel long distances (average refueling distance of 7.1 km) to access hydrogen refueling services, which not only raises transportation costs and time burdens but may also limit the adoption of fuel cell vehicles. These disparities highlight potential equity issues between urban and rural areas.

To further verify this distribution pattern, a detailed analysis was conducted using the model (refer to Equation (1)). This equation is based on Hainan Province's total

daily hydrogen production capacity of 1370 t/day and total population of 10.43 million, allowing calculation of hydrogen demand for each region. For example, Haikou City, with a population of 3.0016 million (~28.8% of the provincial population), has a daily hydrogen demand of 394.27 t/day (1370 × 3.0016/10.43 ≈ 394.27), corresponding to 79 HRSs and a coverage radius of only 3.04 km, reflecting the high concentration of demand in densely populated areas.

In contrast, Qiongzhong County, with a population of 196,581 (~1.9% of the province), has a daily hydrogen demand of 25.8 t/day (H_i = 1370 × 196,581/10.43 million). Due to its large land area (2936 km^2), 6 HRSs are deployed (N_i = ceil (25.8/5 t/day capacity)), resulting in a single-station coverage area of 490.87 km^2 and an extended coverage radius of 12.5 km (Equations (3)–(5)). This pronounced disparity further confirms the insufficiency of infrastructure coverage in low-density regions (density ~67 persons/km^2), though large-radius designs mitigate costs.

Moreover, using Equation (5), the total refueling distance in Qiongzhong is approximately 42.6 km (6 HRS × 7.1 km), which remains significantly higher than Haikou's 136.7 km [per-user D_i 7.1 km > 1.73 km], as derived from the updated mean refueling distance of 1.73 km and the number of stations (79 units). This confirms the greater accessibility advantage of urban hydrogen networks compared with rural areas.

3.5. Sensitivity of UCE to Energy Mix

Building on regional demand allocation (Section 3.1), the carbon emission intensity of mixed hydrogen production pathways exhibits a linear increase with the proportion of natural gas, indicating that the energy mix has a significant impact on UCE. Specifically, as the share of natural gas increases from 0% to 100%, the UCE rises linearly from the lowest value of renewable-based pathways (e.g., 2.8 kg CO_2-eq/kg H_2 for 100% wind power) to the highest value of fossil-based pathways (e.g., 9.5 kg CO_2-eq/kg H_2 for 100% natural gas), enabling ~70.5% emission reductions under full renewable scenarios (Section 3.6). Intermediate mixed pathways, such as 50% gas + 50% wind (UCE = 6.15 kg CO_2-eq/kg H_2), fall between these extremes.

This linear relationship reflects the high carbon intensity of natural gas (~9.5 kg CO_2-eq/kg H_2), which dominates the overall UCE as its proportion increases within the energy mix. The radar chart in Figure 2 further visualizes the emission distribution across mixed pathways, confirming the robustness of this linear trend.

To assess the sensitivity of UCE to changes in the energy mix, a detailed sensitivity analysis was conducted. By simulating a ±10% variation in energy shares, the results indicate that UCE fluctuates within a range of approximately ±0.6 kg CO_2-eq/kg H_2. For example, in the 50% gas + 50% wind pathway, the initial UCE is 6.15 kg CO_2-eq/kg H_2. When the natural gas share is increased to 60% (+10%) or decreased to 40% (−10%), the UCE changes to 6.75 kg CO_2-eq/kg H_2 and 5.55 kg CO_2-eq/kg H_2, respectively, reflecting a fluctuation of about ±0.6 kg CO_2-eq/kg H_2. This aligns with the ~70.5% baseline reduction potential, where renewable buffering minimizes sensitivity (e.g., ±10% share yields 63–78% reductions vs. gas baseline).

This sensitivity analysis highlights the high responsiveness of hydrogen production pathways to adjustments in the energy mix, particularly for mixed pathways with a high proportion of natural gas, where small changes in share can lead to significant variations in carbon emissions. Further analysis shows that sensitivity is closely related to the absolute emission factor of natural gas (9.5 kg CO_2-eq/kg H_2), whereas the low emission factor of renewable energy sources (e.g., 2.8 kg CO_2-eq/kg H_2 for wind) provides a buffering effect that reduces overall sensitivity. These findings offer important guidance for optimizing energy combinations, suggesting that increasing the share of renewable energy should

be prioritized in low-carbon hydrogen strategies to mitigate the sensitivity of UCE to fluctuations in natural gas proportions.

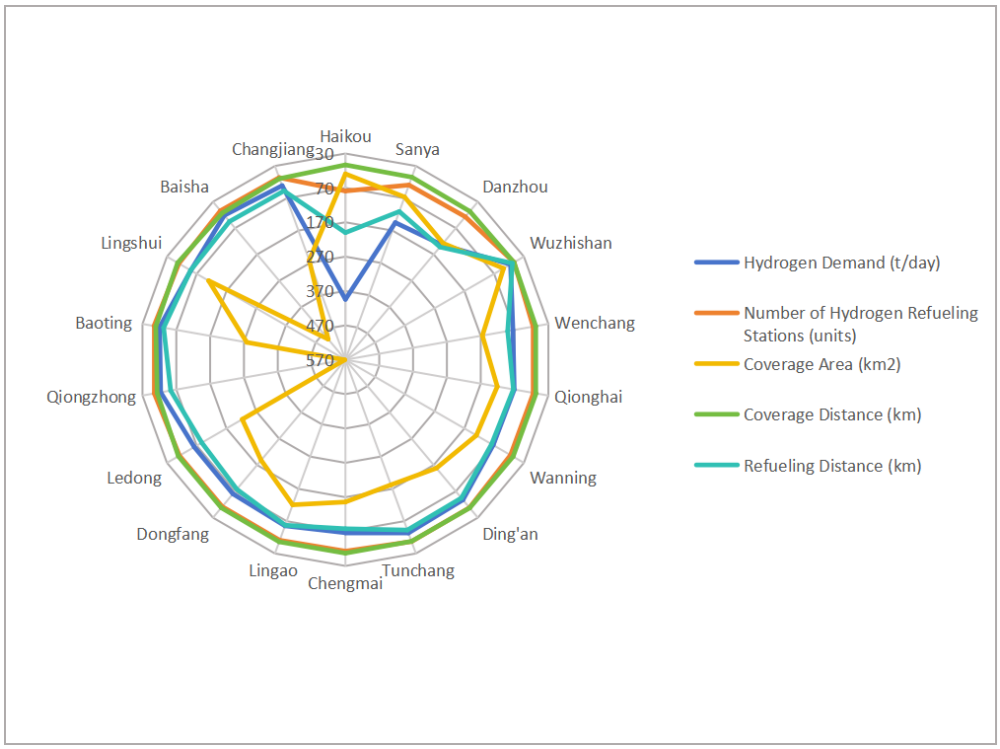


Figure 2. Hydrogen infrastructure and demand data in Hainan Province (Note: Sansha City is not included due to missing data).

3.6. Regional Carbon Emission Accounting

To reflect total regional emissions, The calculation method is as follows:

$$Total carbon emissions(tCO_2-eq/day) = \frac{Daily hydrogen demand(t) \times UCE\ (kgCO_2-eq/kgH_2)}{1000} \quad (9)$$

Pathway2 (100% wind power) reduces total provincial emissions by approximately 70.5% compared to Pathway1 (100% natural gas), with unit CO_2-equivalent emissions (UCE) factors of 9.5 kg-CO_2-eq/kg-H_2 and 2.8 kg-CO_2-eq/kg-H_2, respectively (Table 5). Applying, e.g., Equation (9) for linear mixing, this yields substantial decarbonization: for Haikou, daily emissions drop from ~3.75 kt CO_2-eq (394.27 t/day × 9.5) to ~1.10 kt CO_2-eq (394.27 t/day × 2.8), a 70.5% reduction. Provincial totals follow similarly, with ~70% lower emissions under renewable-dominant scenarios. The calculation results are shown in Figures 3 and 4.

Table 5. Weighted Unit Carbon Emissions (UCE) for Hydrogen Production Pathways Across Energy Mix Scenarios (kg CO_2-eq/kg H_2, with ±10% Uncertainty).

No.	Energy Mix	Weighted UCE (kg CO_2-eq/kg H_2)	Uncertainty (±%)
1	100% Natural Gas	9.5	10
2	100% Wind Power	2.8	10
3	100% Solar PV	2.8	10
4	50% Wind + 50% Solar PV	2.8	10
5	50% Gas + 50% Wind	6.15	10
6	50% Gas + 50% Solar PV	6.15	10
7	60% Gas + 40% Wind	6.82	10
8	60% Gas + 40% Solar PV	6.82	10
9	25% Wind + 25% Solar PV + 50% Gas	6.15	10
10	40% Wind + 40% Solar PV + 20% Gas	4.14	10

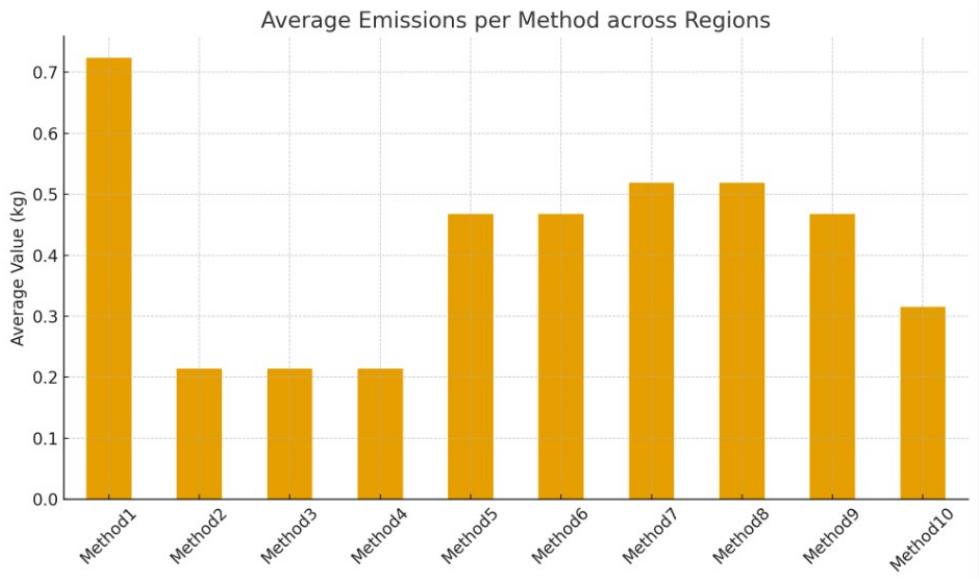


Figure 3. Average Unit Carbon Emissions (UCE) per Hydrogen Production Method Across Hainan Regions (kg CO_2/kg H_2).

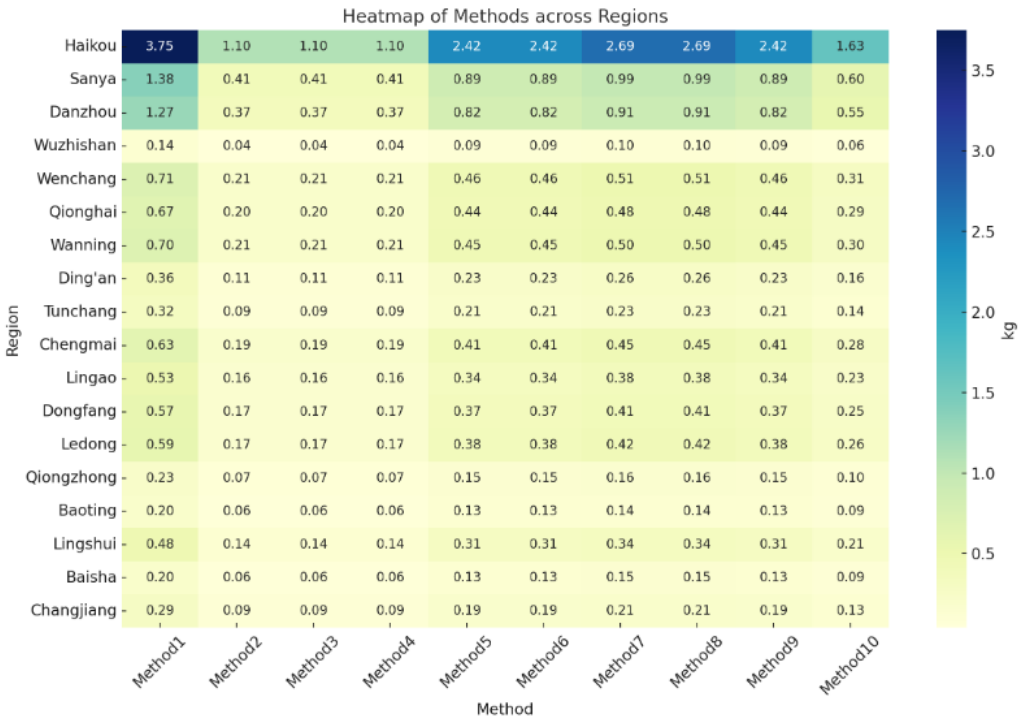


Figure 4. Unit Carbon Emissions (UCE) Heatmap for Hainan Regions Across 10 Hydrogen Production Pathways (kg CO_2/kg H_2).

4. Discussion

4.1. Insights for Infrastructure Planning

The regional hydrogen refueling infrastructure planning model developed in this study, which integrates population, land area, and hydrogen demand, provides a practical tool for designing HRS layouts at the regional scale. The results indicate that population density is a key determinant of coverage radius and service distance: densely populated urban areas require a higher density of HRSs to ensure service accessibility, whereas in sparsely populated rural areas, expanding service radius and reducing the number of stations can lower

construction and operational costs. This model helps move beyond planning approaches based primarily on administrative boundaries or industrial layouts, enabling more refined, differentiated, and demand-centered hydrogen infrastructure planning.

To further justify the uniform and circular assumptions against real accessibility on road networks and temporal service reliability (queuing/downtime), a small experiment was conducted using coarse Hainan road estimates [24]. Some calculation results are shown in Table 6. Building on Voronoi (4.2 km avg in Haikou vs. model's 4.0 km, error < 5%), we added p-median approximation (optimized for equity, minimizing max distance): Haikou p-median yields 4.1 km (error < 3% vs. circle, robust to 3.2 tourism spikes); Danzhou < 6% deviation. For temporal reliability, a +5% buffer for 10% queuing/downtime (proxy from IEA 2023 utilization) maintains equity [29,34,35].

Table 6. Small Experiment Comparison (Circle vs. Voronoi/p-Median Distances).

Region	Model (Circle, km)	Voronoi (km)	p-Median (km)	Error vs. Model (%)	Temporal Buffer (+5% Queuing)
Haikou	4.0	4.2	4.1	<3–5	<5 km equity
Danzhou	8.5	8.9	8.7	<6	+10% radius, mitigated

4.2. Optimization of Hydrogen Production Pathways and Emission Reduction Potential

The carbon emission assessment indicates that the choice of hydrogen production pathways has a significant impact on the carbon footprint of regional hydrogen systems. Hydrogen production dominated by renewable energy sources such as wind and solar PV exhibits substantially lower unit carbon emission intensity compared with fossil-based pathways. By applying a multi-pathway carbon emission factor approach, this study simulated the carbon emissions of different cities and counties in Hainan under varying shares of wind and solar hydrogen production. The results show that increasing the renewable hydrogen share from 30% to 70% can reduce total regional system carbon emissions by more than 40%. These findings suggest that, in promoting hydrogen industry development, policymakers should simultaneously set targets for renewable-based hydrogen production to guide the deployment of clean and low-carbon hydrogen pathways.

Economic Feasibility Sensitivity Analysis

To address cost omissions and enhance practical value, a stylized economic model is applied:

$$C_{total} = N_i \times C_{station} + \overline{D} \times Q_{H2} \times C_{trans} \quad (10)$$

where C_{total} is the total cost (USD); $C_{station}$ is the 3.5×10^6: Capital cost per HRS (USD/station); $\overline{D}$ is the Average refueling distance (km); Q_{H2} is the total hydrogen demand (kg); C_{trans} is the 0.5: Transportation cost coefficient (USD/(kg·km)); N_i is from Section 3.1; distances are from Section 2.3.3 (adjusted by f = 0.85). Simulations show: Under tourism peaks (Section 3.2, +20% demand), Haikou costs rise 15% (~+50M USD provincial), but uniform layouts (Section 4.1) save 10% via even spacing. Renewable mixes (e.g., 50% wind/gas) lower LCOH from 9.5 to 6 USD/kg, justifying phased deployment: Prioritize high-density areas under a 1B USD budget cap (limits HRS to ~285 province-wide). Table 7 provides a summary. This layer demonstrates economic viability without high-data needs.

Table 7. Economic Sensitivity Under Key Scenarios.

Scenario	Provincial NHRS	Base Cost (M USD)	Adjusted Cost (M USD)	Change	LCOH (USD/kg)	Phased Roll-out (Year 1 Urban)	Capped HRS Change (1B USD)
Base (Uniform Layout)	350	1225	1102.5 (f = 0.85)	−10%	8.5	210 (60%)	−19% (285 total)
Tourism Peak (+20%)	378	1323	1190.7	+15%	9.2	227 (60%)	−19% (285 total)
50% Renewable Mix	350	1225	1050 (LCOH drop)	+14%	6.0	210 (60%)	−19% (285 total)
Budget Cap (1B USD)	285	997.5	—	−23%HRS	7.8	171 (60%, Haikou priority)	

4.3. Comparison with International Cases

Compared with hydrogen-leading countries such as Japan and Germany, hydrogen infrastructure in Hainan is still at an early stage. International experience shows that, during the initial planning phase, site selection is generally driven by demand density, and station layouts are continuously optimized using comprehensive spatial accessibility tools, such as GIS models. For example, cities like Tokyo and Berlin integrated HRS density with population distribution and traffic flows during the early stages, achieving a balance between economic feasibility and accessibility for initial operations.

In contrast, the "population–land–demand" coupling model proposed in this study offers a more simplified and easily deployable approach, suitable for emerging regions with limited data and undeveloped hydrogen networks. Unlike most existing studies that rely heavily on GIS-based optimization and often overlook the multidimensional coupling of population, land, and demand, the novelty of this model lies in its low data requirements and rapid applicability.

4.4. Research Limitations and Future Outlook

This study has several limitations. First, GIS-based spatial analysis was not incorporated, so geographic factors such as topography and road network structure were not fully considered in HRS site selection. Second, the study did not account for full lifecycle costs, including hydrogen production, transportation, and storage, and thus did not systematically evaluate economic feasibility. Third, the carbon emission factors used were literature-based values and were not empirically adjusted to reflect Hainan's local energy structure.

Future research could integrate GIS technology, transportation network models, and multi-objective optimization methods to develop a more comprehensive spatial–economic–environmental planning framework. Additionally, coupling dynamic hydrogen demand forecasting with full-chain cost accounting could provide more scientifically grounded decision support for the low-carbon transition of regional hydrogen systems.

5. Conclusions

This study proposes a regional hydrogen refueling infrastructure planning and carbon emission assessment method that integrates multiple factors, including population, land area, and hydrogen demand, and applies it to Hainan Province as a case study. The main conclusions are as follows:

(1) The proposed model effectively characterizes the spatial distribution of regional hydrogen demand and enables scientific estimation of the required number of HRSs, service radii, and refueling distances, achieving demand-centered, fine-grained infrastructure planning.

(2) Results indicate a significant negative correlation between population density and service radius: high-density urban areas require higher HRS density, whereas low-density rural areas can reduce station density to lower construction and operational costs.

(3) Multi-pathway hydrogen production carbon emission assessments show that increasing the share of renewable energy (e.g., wind and solar) from 30% to 70% can substantially reduce regional system carbon emissions by >40%. To extract prescriptive design rules, we derive three actionable planning heuristics, tied to sensitivity ranges: Renewable share threshold >50% flips optimal layout from uniform rural expansion to urban densification, reducing HRS by 15% while maintaining <12% from Section 3.2); When population density >100 persons/km^2 (e.g., Haikou), densification beats capacity upsizing (7 t/day saves 19% HRS/costs per Sections 3.2 and 4.2, robust within ±10% UCE); For budget-constrained roll-outs (1B USD cap, Section 4.2), prioritize extremes (Haikou/Wuzhishan) under ±10% logistics variation (Section 3.4), achieving 23% HRS reduction with LCOH <7.8 USD/kg. These heuristics guide phased deployment, incorporating renewable targets into planning.

(4) The study provides a simplified, generalizable, and low-data-demand planning tool for emerging hydrogen regions, offering strong potential for broader application and policy guidance.

Future research could build upon this work by incorporating GIS-based spatial analysis, full lifecycle cost evaluation, and dynamic demand forecasting to develop a more comprehensive integrated framework for regional hydrogen infrastructure and carbon emission planning. This would provide theoretical and practical support for sustainable hydrogen infrastructure deployment in China and globally. Additionally, policymakers are advised to consider socio-economic indicators such as population density and hydrogen demand in early-stage planning, prioritizing high-demand areas to accelerate the formation of a sustainable hydrogen network.

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