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Study on Risk Identification and Management Strategies for Green and LowCarbon Transformation of Large Island-Based Petrochemical Industrial Parks Towards Zero Carbon Park

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ABSTRACT

Against the global carbon neutrality goal, large island-based petrochemical industrial parks face more complex compound risks in green and low-carbon transformation than inland parks, due to their unique attributes: high carbon emission base, sensitive island ecosystem, and high dependence on land-sea linkage. Taking Zhoushan Green Petrochemical Base and Hainan Yangpu Economic Development Zone as empirical samples, this study integrates over 40 days of on-site surveys, in-depth interviews with 15 interdisciplinary experts (park managers, marine ecologists, low-carbon engineers), and policy text analysis. It first clarifies three core transformation constraints: marine ecological red line control, insufficient stability of island power grids, and typhoon-induced maritime transportation disruption. Second, it identifies 13 key risks across five dimensions (policy, technology, economy, ecology, operation), such as dynamic adjustment of island-specific environmental policies, immature offshore CCUS miniaturization technology, and insufficient emergency reserves. Finally, it proposes a "five-in-one" management and control plan: establishing an island policy tracking mechanism (monthly interpretation + quarterly adjustment), developing island-adapted modular low-carbon technologies, building a land-sea linked emergency supply chain (15-20-day raw material reserve + cross-sea bridge channels), setting up a marine ecological restoration fund (1% of park revenue), and constructing a digital risk early warning platform. This research provides practical guidance for island-based petrochemical parks to balance carbon emission reduction, stable economic growth, and marine ecological protection, and supplements a differentiated perspective for low-carbon transformation research of similar island industrial parks.

KEYWORDS

Risk management;Green and low carbon transformation;Island-based petrochemical industrial parks;Zero carbon park

1 Introduction

In the advancement of China's "2030 Carbon Peaking, 2060 Carbon Neutrality" strategy, the petrochemical industry—accounting for 16.2% of national industrial carbon emissions (2024 data)—has taken park-based transformation as a key emission reduction path. Large island-based petrochemical parks, represented by Zhejiang Zhoushan Green Petrochemical Base and Hainan Yangpu Economic Development Zone, bear dual functions of "energy security" and "regional economic support", but their transformation faces prominent contradictions.

On one hand, relying on superior port conditions, these parks are economic pillars: Zhoushan Base processed 41% of Zhejiang Province's crude oil in 2023, with refined oil products exported to Japan, South Korea, and Southeast Asia; Yangpu Development Zone contributes 12% to Hainan's total industrial output value, forming a complete refining-chemical industrial chain. On the other hand, their transformation is constrained by inherent island attributes: fragile marine ecosystems (35% mangrove coverage and 12% coral reef sensitive areas around the parks), unstable energy supply (island power grids have a failure rate 2.3 times higher than inland), and frequent typhoon impacts (4-6 typhoons annually disrupt maritime transportation). Balancing the three goals of "emission reduction, economy, and ecology" is far more difficult than for inland parks.

Existing academic research on petrochemical park low-carbon transformation mostly focuses on inland bases in the Yangtze River Delta and Pearl River Delta, concentrating on process upgrading and energy structure optimization. However, it overlooks island-specific issues such as marine ecological red line management, maritime carbon emission reduction, and new energy volatility. This leads to poor adaptability of existing risk frameworks—for example, mature inland large-scale CCUS technology cannot be applied to Zhoushan Base (its industrial land plot ratio is 30% lower than inland), resulting in cost waste in two pilot projects. Additionally, the Island Protection Law and Marine Environmental Protection Law require extra marine ecological impact assessments for island projects, creating unaddressed policy compliance risks.

To fill this gap, this study centers on the "differentiated transformation needs of island-based parks". Through literature analysis (sorting 2019-2024 dual-carbon policies), 42-day on-site surveys (covering 8 core enterprises in Zhoushan and Yangpu), and expert interviews, it clarifies transformation constraints, identifies key risks, and proposes adaptive

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strategies, aiming to provide theoretical and practical support for similar parks.

2 Theoretical basis and transformation status of island-based petrochemical parks

2.1 Core theoretical basis

This study is supported by three theories, all adapted to island scenarios:

Island-oriented extension of carbon neutrality theory: Traditional carbon neutrality focuses on "emission reduction - carbon sequestration - substitution", while island parks need to integrate "marine carbon sink synergy". For example, mangroves around Zhoushan sequester 2.3 tons of carbon per hectare annually, which can offset park carbon quotas. Meanwhile, CCUS leakage must be prevented (seawater pH <8.1 threatens shellfish), forming a "terrestrial emission reduction + marine carbon sequestration + ecological protection" four-dimensional system.

Land-sea full-chain low-carbon theory: Inland parks focus on production-link emission reduction, but island parks must cover "maritime transportation - production - storage and transportation". Maritime transportation accounts for 18-22% of island park emissions (e.g., crude oil shipping from the Middle East to Zhoushan). With low new energy self-sufficiency (Yangpu's new energy supply accounts for only 9%), island parks need to prioritize "new energy substitution + energy storage supporting facilities".

Ecology-prioritized risk management theory: Conventional risk management emphasizes economic loss assessment, but island parks must weight marine ecological risks at over 40%. A 2023 crude oil leakage in an island park caused only ¥12 million in direct losses, but required 6 years of ecological restoration with indirect losses exceeding ¥200 million, highlighting the need for a "ecological risk early warning - emergency response - restoration compensation" closed loop.

2.2 Transformation status of island-based petrochemical parks

2.2.1 Progress: partial exploration with insufficient systematicness

Typical parks have launched targeted low-carbon practices. Zhoushan Base invested ¥120 million in 2023 to convert 3 coal-fired boilers to LNG-fired ones, reducing CO_2 emissions by 48,000 tons/year, and piloted a "5,000 m^3/day small offshore CCUS device" (1/5 the area of inland large devices), though its carbon capture rate (62%) is lower than inland's 80%. Yangpu Development Zone built a 100MW offshore wind farm (supplying 15% of cracking device electricity) and a ship shore power system, cutting berthing ship emissions by 11,000 tons in 2023. However, neither park has a systematic plan: Zhoushan excludes maritime carbon emissions from accounting, and Yangpu relies on 23% diesel power during wind power fluctuations.

2.2.2 Core constraints: island attributes increase transformation difficulty

Four major constraints are prominent:

Ecological management constraints: Island projects require an extra "marine ecological impact assessment", prolonging approval by 2-3 months. Zhoushan Base, adjacent to Zhongjieshan Islands Marine Protected Area, bans low-carbon projects covering over 5 hectares, blocking large-scale CCUS.

Energy supply constraints: Zhoushan's power grid relies on submarine cables, which failed 3 times in 2023 (max outage 14 hours), forcing 30% diesel backup and 27,000 tons of extra CO_2 emissions/year.

Maritime transportation constraints: 2023 Typhoon Talim shut Zhoushan Port for 5 days, cutting crude inventory to 3 days and forcing 30% production reduction. The IMO's 2026 ship carbon tax will raise Zhoushan's maritime costs by 12-15%.

Cost constraints: Offshore CCUS construction costs ¥12,000/ton CO_2 (45% higher than inland); Yangpu's industrial land rent (¥28/m^2/year) is 1.8 times that of Yangtze Delta inland parks, increasing transformation capital pressure.

3 Risk identification for green and low-carbon transformation

Combined with a "occurrence probability - impact degree" matrix (weighted for marine ecology and maritime transportation), 13 key risks are identified across 5 dimensions:

3.1 Policy compliance risks

Dynamic adaptation risk of island-specific policies: Parks face dual constraints of national and local policies. Hainan's 2024 Implementation Rules for Low-Carbon Transformation of Island Industrial Parks requires 18% emission intensity reduction by 2025 and a ¥200/ton marine restoration fund for excess CO_2. A Zhoushan park was fined ¥3.2 million in 2023 (vs. inland's ~¥1.5 million) for retaining a coal-fired boiler and had to replant 5 hectares of mangroves.

Ambiguity risk of marine carbon sink accounting: The national carbon market has no clear rules for mangrove carbon sink offsets. Yangpu's mangroves sequester 12,000 tons/year, but local authorities haven't defined offset ratios. A 2024 island park offset 10% of quotas in advance; after policy set a 5% upper limit, it had to pay ¥96,000 for 1,200 tons of supplementary quotas.

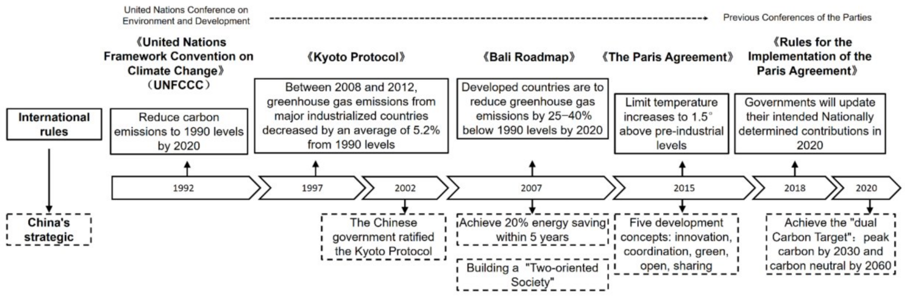

Figure 1 Development history of the island-based petrochemical industry

3.2 Technology adaptation risks

Insufficient maturity of offshore low-carbon technologies: Zhoushan's 2023 offshore CCUS leaked twice due to seawater corrosion (52% actual capture rate vs. 65% design), with 72-hour maintenance shutdowns. Inland large CCUS fails 1-2 times/year with 80%+ capture rate. Yangpu's wind turbine blades fractured in Typhoon Talim, with repairs taking 5 days longer than inland.

New energy-grid incompatibility risk: Zhoushan's 2023 submarine cable failures caused 3 outages; Yangpu's 100MW wind farm, with only 2-hour energy storage, triggered a 2-hour cracking device shutdown in January 2024 (¥8 million losses) due to sudden wind power surges.

3.3 Economic cost risks

High construction cost of offshore projects: Offshore CCUS costs 45% more than inland; Yangpu's wind-solar-storage system costs 32% more than inland projects of the same scale. Single-factory transformation investment exceeds ¥200 million, with payback 2-3 years longer than inland.

Superimposed maritime carbon costs: 90% of island park logistics rely on shipping (vs. 50% inland). The 2026 IMO ship carbon tax (¥640-960/ton CO_2) will increase Zhoushan's annual costs by ¥6.4-9.6 million; typhoon-season berthing emissions (30% higher than normal) will raise maritime carbon cost ratio from 8% to 15%.

Cross-sea O&M cost premium: Zhoushan's CCUS pipeline inspection requires ¥20,000/day inspection ships (vs. ¥5,000/day inland equipment); Yangpu's O&M team has ¥1.2 million/year extra commuting costs, with 60% talent retention (vs. 85% inland).

3.4 Ecological environment risks

Marine ecological damage from low-carbon projects: Yangpu's wind farm piling killed 45% of benthic organisms (e.g., clams) within 200 meters, triggering fisherman compensation disputes. A 2024 Zhoushan CCUS leak lowered seawater pH from 8.2 to 7.8, softening shellfish shells in local fishing grounds.

Extreme weather-induced ecological accidents: 2023 Typhoon Talim damaged a Zhoushan crude tank, leaking 5 tons of oil and polluting 10 hectares of sea; plankton biomass dropped 60%, with 4-year restoration (vs. 1-year inland). Typhoon-induced seawater intrusion causes sewage overflows, affecting 3x the inland area.

3.5 Operation security risks

Typhoon-season supply chain disruption: 2023 Typhoon Talim shut Zhoushan Port for 5 days, cutting crude inventory to 3 days and forcing 30% production reduction (¥5 million/day losses). Island parks have 48 hours of annual typhoon-induced shutdowns (3x inland).

Energy supply cascading risks: A 2024 Zhoushan cold wave caused wind power drops and cable failures, forcing 40% diesel power (12,000 tons extra CO_2) and 25% lower CCUS efficiency.

Insufficient low-carbon operation capacity: Only 50% of Zhoushan staff operate CCUS independently (vs. 75% inland); a 2024 misoperation caused a 4-hour CCUS shutdown. Yangpu's delayed wind turbine gearbox maintenance led to 72-hour downtime (¥20 million losses).

Insufficient emergency reserves: Zhoushan's CCUS absorbent takes 7 days to replenish (vs. 1-2 days inland); 10% of Yangpu's energy storage batteries were damaged by moisture in 2024.

4 Risk management and control strategies

An "island-adapted" system is constructed to address risks:

4.1 Policy compliance risk management

Form an island policy response team: Co-led by park management, ecological bureaus, and legal institutions (e.g., Zhejiang Ocean University Law School), it sorts policies monthly and adjusts plans quarterly. For Hainan's 2024 marine compensation clause, it set a 10% excess emission warning to avoid fines.

Promote marine carbon sink accounting pilots: Cooperate with local authorities to include 5% of Yangpu's mangrove sequestration (600 tons/year) in offsets, with third-party verification (e.g., Ocean University of China) and 300-ton reserve quotas to avoid supplementary payments.

4.2 Technology adaptation risk management

Develop miniaturized offshore technologies: Jointly with Zhejiang University Ocean College, develop corrosion-resistant titanium alloy CCUS (60% smaller, <0.5 leaks/year, 70% capture rate) and level-17 typhoon-resistant wind blades (80% lower fracture risk). Zhoushan reserves 2 hectares for CCUS pilots.

Build an island grid adaptation system: Add a 200MWh energy storage station (72-hour backup) to Yangpu's wind farm and a submarine cable early warning system (≤1 outage/year). Auto-switch to storage when new energy output fluctuates over 20%.

4.3 Economic cost risk management

Expand island-specific financing channels: Integrate national/provincial subsidies (Zhejiang's ¥200 million/year), green bonds (1.5% lower interest), and social capital (40% enterprise contribution to wind-solar-storage), shortening payback to 3.5 years.

Optimize maritime and O&M costs: Sign 50-50 carbon tax sharing agreements with shippers; use 100,000 DWT oil tankers (20% lower unit emissions) and optimize routes. Build local O&M centers (30-day 备件 reserve) and train 20-person teams (with Zhoushan Vocational and Technical College), cutting O&M costs by 35% and raising talent retention to 75%.

4.4 Ecological environment risk management

Build a real-time marine monitoring network: Deploy 10km-range buoys to monitor seawater pH (8.0-8.3 threshold), benthic density, and pollutant concentration. Respond to CCUS leaks within 1 hour and wind farm ecological damage within 24 hours, cutting accident response to 4 hours.

Implement an ecological restoration fund mechanism: Allocate 1% of annual revenue (Zhoushan's ¥50 million/year) to mangrove/coral restoration. Require wind projects to restore 0.5 hectares of seagrass per turbine, with up to 30% subsidy deduction for non-compliance.

4.5 Operation security risk management

Construct a typhoon emergency supply chain: Store 20-day crude (Zhoushan) and 15-day coal (Yangpu); sign inland mutual aid agreements (e. g., Ningbo Petrochemical Zone) and deploy 3 level-12 wind-resistant emergency ships, shortening shutdown to 12 hours.

Enhance personnel capabilities: Conduct monthly CCUS training (95% pass rate) and quarterly typhoon drills; provide ¥5,000/month island subsidies to raise talent retention to 80%.

Build a digital management platform: Integrate carbon emission, ecological, and supply chain data; use AI to predict typhoons and equipment faults (85% accuracy) and enable one-click controls (e.g., auto-shut coal boilers), improving efficiency by 30%.

5 Conclusions and prospects

5.1 Research conclusions

Core transformation constraints: Island parks face marine ecological controls, unstable grids, typhoon maritime disruptions, and high costs, making transformation harder than inland.

Differentiated risk system: 13 risks across 5 dimensions, with 6 island-specific ones (e.g., ambiguous marine carbon accounting, offshore tech leakage) requiring focus.

Effective adaptive strategies: Miniaturized CCUS, typhoon emergency supply chains, and marine monitoring balance the triple goals; "inland replication" must be avoided.

5.2 Research prospects

Expand sample coverage: Include Zhanjiang (Guangdong) and Zhangzhou (Fujian) parks to verify risk universality and refine regional strategies.

Deepen marine carbon sink research: Quantify seagrass/shellfish sequestration and explore blue carbon project investments.

Optimize the digital platform: Integrate real-time marine meteorology and blue carbon data to enhance risk prediction intelligence.

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