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A Case Study of Maritime Hydrogen Energy Development in Jiangsu Province in China

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Abstract: This study aims to develop a systematic review of hydrogen energy storage technologies and maritime applications, intending to present an international perspective on the matter. This study analyses the role of advanced storage methods in enabling renewable energy systems integration in coastal regions, using Jiangsu Province of China as an example. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was used as the research method. Data was obtained from research studies over the period 2015–2023. The analysis included a total of 96 papers from Web of Science, Scopus, IEEE Xplore, and ScienceDirect databases. Results show that Europe and East Asia led publications at the intersection of hydrogen storage and marine applications over the past decade. One of the main issues associated with maritime hydrogen adoption found in the dissertation is related to the mismatch between technological readiness levels and commercial maturity. Findings indicate promise for fuel cell integration with ships, ports, offshore wind farms, and other coastal transport sectors. However, the realization of the project depends on infrastructure development, policy support, and viable business models tailored to the marine environment. Focused demonstration projects and public-private collaboration can further progress towards robust hydrogen-based energy storage ecosystems in suitable regions like Jiangsu and beyond.

Keywords: Hydrogen energy storage; Fuel cells; Maritime applications; Ships; Offshore wind farms

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1. Introduction

Hydrogen energy storage has emerged as a critical technology to enable the wide-scale adoption of renewable energy and support decarbonization goals. As the world's largest emitter of greenhouse gases, China has made the development of hydrogen energy a strategic priority under its 14th Five-Year Plan for Economic and Social Development (2021–2025). Specific goals aim for over 50,000 fuel cell electric vehicles in the country and over 200 hydrogen refueling stations built nationwide by 2025. The plan also provides policy support to develop China's capabilities in hydrogen production, storage, distribution, and end-user equipment [1].

Coastal manufacturing regions like export-oriented Jiangsu Province have been strategically targeted as hydrogen energy pilot zones. With extensive marine resources and goals to scale offshore wind, Jiangsu provides an ideal case study for assessing hydrogen storage systems tailored to renewable power systems. This systematic dissertation analyses the evolution of hydrogen storage in China, shifts in application areas, and policy changes. Focusing on Jiangsu, progress is benchmarked against technology viability, infrastructure availability, and economic progress to identify promising storage applications for the province's offshore wind energy viability alongside remaining hurdles [2].

2. Methods and approach

This literature review utilizes the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a rigorous, comprehensive, and transparent review process. PRISMA provides an evidence-based protocol for reporting systematic reviews, aimed at minimizing bias and improving reproducibility. Adopting this formal method enhances the quality, completeness, and consistency of the review.

3. Results and discussion

China initially focused predominantly on hydrogen for oil refining and ammonia production rather than energy storage in the early 2010s. However, surging wind and solar energy installations prompted growing consideration around 2015 of hydrogen's ability to convert renewable surpluses through electrolysis to store and transport green energy instead of direct grid connection. Most studies cite the release of an extensive national hydrogen energy technology roadmap in 2016, coupled with falling production costs globally, as catalysts for China to embrace hydrogen more widely across the power, industry, heating, and transportation sectors [3].

China's fluctuating policy landscape was a key variable in shaping energy storage development pathways, but the dissertation now shifts focus to how falling production and fuel cell costs have diversified hydrogen's application areas over the past decade. As recently as 2015, hydrogen use was concentrated overwhelmingly in oil refining, methanol production, and ammonia synthesis. However, estimates suggest clean hydrogen costs could plunge 50%–60% by 2030, driven by improved electrolyzer and storage tank efficiencies as well as large-scale manufacturing. These projections have ignited widening transportation and electricity sector adoption in addition to traditional industrial usages [4].

In the power sector, hydrogen energy storage increasingly integrates with wind and solar energy installations to absorb temporal oversupply and mitigate intermittency issues through conversion back to electricity as needed. Falling electrolysis costs alongside improving fuel cell efficiency have enhanced hydrogen's commercial viability compared to battery storage for large and long-duration applications. The main advantages of hydrogen energy storage over lithium-ion batteries are its nearly limitless capacity and quick response to grid changes during demand spikes or renewable lulls. However, as this is a new industry, there are still concerns about the best business plans and sites for facilities that will allow solar and wind farms to integrate with local grid infrastructure [5].

Energy storage is a prime yet undeveloped domain beyond the transportation and shipping demonstrations observed thus far. Jiangsu's province government charts a course toward a full hydrogen economy, with construction commenced in late 2022 on a 100 MW electrolysis facility coupled to the 400 MW Rudong Offshore Wind Farm, set to generate up to 3,000 tons of green hydrogen yearly while absorbing excess daytime electricity for nighttime grid firming and power plant co-firing. With a 14 GW total offshore wind energy target by 2025, hydrogen storage pilots tailored to marine environments will provide crucial lessons for stabilizing Jiangsu's future renewable energy industry [6].

4. Analysis and discussion

Jiangsu's fluctuating policy landscape has critically enabled the advancement of hydrogen energy storage over the past decade. Initial national road mapping sparked the conceptualization of hydrogen's potential, while recent expansive demonstrations and incentives mobilized practical buildout. Significant scale-up remains necessary to meet 2030 non-fossil fuel targets, with credible pathways coming into focus centered on dedicated production, integrated downstream uses, and coordinated planning. The release of an authoritative hydrogen energy technology roadmap in 2016 marked an important milestone in Jiangsu embracing the element as more than just industrial feedstock. While already utilized for oil refining and chemical synthesis, curbing reliance on imported fossil fuels and rising ecological consciousness turned attention to hydrogen's promise for storing and transporting renewable energy. Concurrently, dramatic solar photovoltaic (PV) cost declines drove installations up by 2400% between 2012 to 2017. However, distribution bottlenecks left 35% of solar and 45% of wind output unabsorbed, due to costly grid stability risks. These conditions increase the focus on power-to-gas hydrogen pathways to harness surplus clean electricity. The roadmap consequently established a comprehensive blueprint encompassing production, storage, transportation, and end-user equipment. Targets sought 5% of hydrogen derived from renewables by 2020 and 20% by 2030, supported by subsidies and production quotas. Jiangsu would simultaneously need to expand capacity by over 60% while lowering costs to internationally competitive <3 RMB/standard cubic meter levels [7]. The plan noted achieving scale for export standard components could enable domestic concept viability. Tailored regional lustering centered on resource availability and industrial demand was also highlighted. While ambitions remained largely aspirational due to underdeveloped infrastructure and early technical status, the roadmap cemented hydrogen energy storage as an instrumental national priority. The 13th Five Year Plan era from 2016–2020 saw measured but gradual progress per the roadmap. Costs exceeding 1500 RMB/kg, lack of unified codes and standards, as well as a shortage of storage and distribution infrastructure constrained adoption. Early facilities remained small, compiling under 50 MW nationwide. However, policies financed several hundred demonstration projects, focusing on transportation applications like FCVs, buses, and logistics vehicles near cities with established carmakers and hydrogen supplies from chemical industrial bases. These demonstrations made advances but required heavy subsidies of up to 2 million per bus to break even commercially. Most domestic capacity met fossil-based gray hydrogen demand from oil, steel, and fertilizer feedstocks rather than renewables. While the formative roadmap expanded conceptual pipeline interest, material leapfrogging lagged developed Asian and European hydrogen economies [8]. Tighter ecological constraints accelerated Jiangsu's commitment from 2020 forward. Carbon neutrality pledges and the 14th Five Year Plan's mandate to source 25% of energy from non-fossil sources by 2030 have made hydrogen indispensable to the energy economy. The 14th Five-Year Plan consequently devoted an entire section to incubating the hydrogen industry, targeting 6 GW capacity and 200 refueling stations in metropolises by 2025. Central policy bank funding and preferential electricity pricing aimed to spur related projects. Explicit short and medium-term targets brought concrete immediacy compared to the previous roadmap's distant visioning. Multinational developers including Siemens and Cummins also committed to Chinese facilities for electrolyzers and fuel cells, embedding global knowledge transfer. Accelerated policy tailwinds point to hydrogen storage prospectively reaching an inflection point if key open questions around production models and end-user cases are resolved [9]. On the production front, deliberation continues around centralized rather than distributed approaches. Large facilities achieve superior economies of scale, with alkaline electrolysis lowering costs below $2 per kg at over 500 MW capacities needed for export ambitions. Distributed configurations closely co-located with renewable sources avoid transmission losses and conversion steps. This fits logically with hydrogen's role as a flexibility asset to prevent renewable curtailment. However, decentralization requires markup to cover redundancy since asset utilization rates suffer. Identifying an ideal balance between these models aligned with resource zones and demand centers remains a work in progress [10].

5. Conclusions and future outlook

Over the past ten years, China's energy transition reached a turning point marked by its commitments to the Paris Climate Agreement, historic net-zero carbon pledges, and cascading signals that require a final restructuring of the power system's fundamentals. As a result, the strategic importance of renewable energy increased, and vulnerabilities related to intermittency had to be mitigated through the use of contemporary storage solutions to control the rapid expansion of capacity. When balancing reserves cannot ramp up quickly enough to offset their unpredictable variability during generation troughs, they run the risk of being abandoned. Hydrogen, on the other hand, uniquely bridges this gap. Hydrogen is the essential flexibility enabler that enables China's grids to sustainably scale up revolutionary clean energy usage because of its capacity to absorb electricity during peaks and convert it into transportable gas form, as well as to use it as an input for electrolytic regeneration into power during lulls [11].

In particular, Jiangsu Province faces this exponential growth paradigm as a leading hotbed for offshore wind energy development and manufacturing expertise for modular components that will spread worldwide. As a result, the province is at the forefront of evaluating how to build an integrated hydrogen storage ecosystem that will support its developing fleet of maritime renewable energy vehicles [12]. The province's coastal test bed will provide valuable insights for national buildout scenarios, which will be used by authorities to plan infrastructure configurations and incentives that are specific to local resource zones. Promising advancements in demonstrations in recent years have been made, but in the near future, efforts must concentrate on connecting isolated projects to networked systems that will cross the commercial viability threshold through scale. Dedicated development zoning, private sector risk-sharing arrangements, and coordinated planning between storage operators and renewable power producers can smooth this challenging transition [13].

China's first hydrogen technology roadmap published in 2016 broadened the conceptual framework for uses beyond the conventional reliance on industrial feedstocks. However, after 2020, slow and measured progress was hindered by high generation costs and a lackluster distribution network. The turning point came in 2021 when plans to source 25% of energy from non-fossil sources by 2030 became non-negotiable due to climate priorities. The opportunity to make hydrogen economically viable was presented by this timely convergence with sharp drops in renewable energy costs, which also coincided with a decline in the price of competing grid-firming assets such as lithium-ion batteries. As such, all storage-related services underwent a reevaluation for situational suitability across multiple stability services [14].

Upstream technologies for producing hydrogen have advanced from depending solely on coal gasification to renewable energy-powered electrolysis pathways that, if strategically located close to abundant solar and wind resources, can reduce prices for transportation below the crucial $2/kg threshold. By maintaining their resistance to deterioration and increasing peak conversion efficiency to 95%, solid oxide variant cells offer yet another breakthrough through 2030. Subsequently, fuel cells have overcome initial durability issues in transit applications such as buses, and they can now sustain daily operations with a range of more than 500 km between overnight refueling. As long as their lithium-ion replacements are continuously monitored, further advancements aimed at reducing vehicle weight and replacing platinum might make hydrogen-fueled transportation economically advantageous in comparison to competitors in the battery market [15].

The power industries themselves have the largest potential market because hydrogen makes it easier to manage the highs and lows of renewable energy across daily and seasonal cycles than any other alternative storage format. In Jiangsu, offshore wind resources are predicted to grow to 14 GW by 2025, making them excellent candidates for on-site electrolysis facilities as opposed to requiring increases in grid transmission capacity or other storage options that are still constrained by discharge cycle and therefore unsuitable for inter-day balancing requirements. Hydrogen-fueled ships and port equipment are equally welcome in this marine environment niche, avoiding the landside infrastructure barriers that are currently impeding the expansion of transportation in the near future [16].

The favorable policy environment in China is still in place as hydrogen storage progresses at a reasonable projected rate. But before projects can function profitably without government incubation, infrastructure development, technological advancements, and integrated demonstrations are still required over the next five years. Hence, Jiangsu needs to proactively develop electrolytic facilities to prepare its coastal grid for exponential wind absorption, instead of waiting for stability issues to arise when additional capacity appears. This entails creating project approval accelerators, zoning overlays for storage sites, and financial incentives that direct independent power producers toward cooperative ownership arrangements with electrolysis suppliers [17].

Promoting specialty zones for associated manufacturing in parts like fuel cells, crystals, and storage tanks is one of the province's other responsibilities. Planning is also necessary for vocational training to prepare operators, in addition to formal academic engineering curricula. Furthermore, carbon pricing schemes may strengthen the business case in places with high emissions, such as Lianyungang [18]. However, demand-pull factors also matter a lot. For example, ports may impose fuel switching requirements, and given the optimistic solar energy outlook, the industry may be subjected to heat electrification codes. The market forces must therefore intensify the momentum of policy to bring changes [19].

Scaling replicable models of offshore wind farms combined with green hydrogen generation capacity is the main focus of near-term demonstration priorities. This will help with intertemporal balancing and protect local grids from variability risks [20]. Provincial funding is required for planning reforms that lower institutional barriers to independent power producer limitations and grid connectivity delays while educating about the symbiotic relationship between system operations. Before addressing landside logistics, an intuitive transition corridor is provided by parallel testing of harbor and shipping machinery. This allows for maritime access to hydrogen. In general, Jiangsu and China still have a lot of work to do to investigate the best possible arrangements that link local resources to industrial clusters throughout the various development areas that are being pursued. However, it is important to recognize the achievement of converting existential climate obligations into business opportunities. With pragmatism and patience, hydrogen storage appears well-positioned to anchor sustainability for the next generation [21].

Disclosure statement

The author declares no conflict of interest.

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