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Digital Transformation of Portugal's Marine Industry: Practical Logic, Strategic Framework, Challenges, and Implications

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Abstract: Against the backdrop of the global "blue acceleration" and the European Union's twin green and digital transition, Portugal has made the digitalization of its marine industry a strategic lever for national competitiveness. Examining the internal logic and practical constraints of this transformation can provide a country-level reference for the digital development of China's marine economy. Adopting literature analysis and case study methods, and drawing on Portugal's Estratégia Nacional para o Mar 2021-2030 (National Strategy for the Sea 2021-2030, ENM 2021-2030), European Union policy documents, and authoritative statistical data, the study investigates the practical logic, strategic framework, and implementation path of Portugal's marine industry digital transformation, together with the challenges it confronts. The findings show that Portugal has established a "data first" principle at the strategic level; formed a collaborative "government-industry-university-research-finance" network comprising government coordination through the Directorate-General for Maritime Policy (DGPM), financial guidance through the Fundo Azul (Blue Fund), and cluster-based translation of research through Fórum Oceano and the Portugal Blue Digital Hub (PBDH); and pursued implementation through digital infrastructure such as the Atlantic CAM submarine cable system, the SNIMar national data-sharing platform, and blue digital skills programs. Nevertheless, the transformation remains constrained by structural dependence on EU funding, illustrated by the €252 million earmarked for the blue economy under the Recovery and Resilience Plan (PRR) and the contraction of the offshore wind target from 10 GW to 2 GW; by uneven digitalization across sectors dominated by micro, small, and medium-sized enterprises; by barriers to marine data circulation and unresolved data-rights mechanisms; and by the persistent outflow of highly skilled talent. China can draw on Portugal's experience in top-level design and multi-purpose infrastructure while guarding against funding externalization, industrial polarization, and talent loss, so as to optimize its modern marine industrial system.

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1. Introduction

China attaches great importance to the high-quality development of its marine economy, and national planning has made explicit arrangements for the digital and intelligent transformation of the marine economy. In December 2021, the State Council approved the "14th Five-Year Plan for Marine Economic Development" (《"十四五"海洋经济发展规划》), setting requirements for optimizing the structure of the marine economy and raising the digitalization level of marine industries [1]. According to the 2024 China Marine Economic Statistical Bulletin (《2024年中国海洋经济统计公报》), China's gross ocean product reached 10.5438 trillion yuan in 2024, surpassing the 10-trillion-yuan mark for the first time, an increase of 5.9% over the previous year and accounting for 7.8% of GDP, while the digital-intelligent and high-end upgrading of traditional marine industries continued to advance [2]. It is thus evident that applying digital technologies to transform and upgrade traditional marine industries and to foster new quality productive forces in the marine sector has become an important pathway toward high-quality development of the marine economy.

Implementing these arrangements requires both grounding in domestic realities and deep participation in global ocean governance, drawing useful practices from cross-national comparison. Among coastal states, Portugal's marine industry development trajectory and digital transformation practice are representative to a certain degree. As a traditional seafaring nation and an important participant in the EU blue economy, Portugal possesses a maritime jurisdictional area among the largest in the world [12] and, in recent years, has followed the EU's twin green and digital transition strategy, making marine digitalization an important fulcrum for enhancing national competitiveness. Its explorations in smart port construction, three-dimensional marine environmental monitoring, and offshore renewable energy operation and maintenance align with China's policy directions on port digital-intelligent transformation and marine ecological and environmental protection. Portugal was also among the first EU member states to establish a blue partnership with China, and the two sides already have a foundation for cooperation in marine science and technology and port construction; examining its transformation practice is therefore of practical significance for deepening China-Portugal maritime cooperation. From a research perspective, Portugal combines three attributes—traditional seafaring nation, EU member state, and Atlantic gateway—and its transformation practice simultaneously exhibits the constraints faced by small states in ocean governance and the policy transmission mechanisms operating within a regional integration framework, giving it sample significance for understanding the digitalization pathways of medium-sized marine economies.

As the digital economy and the marine economy become ever more deeply integrated, the digital transformation of marine industries has become a focus of scholarly attention. Regarding the mechanisms of digital empowerment, Ma Wenting et al., drawing on Marx's theory of social reproduction, analyzed the two-way linkage mechanism through which the digital economy empowers the high-quality development of the marine economy [3]; Liu Shuguang et al. verified that digitalization can promote the transformation and upgrading of marine industries, with effects displaying marked regional heterogeneity [4]. Regarding policy support and spatial layout, Li Xiaoshu et al. argued that escaping industrial dilemmas urgently requires a digital innovation policy support system encompassing institutional safeguards and multi-actor coordination [5]; Shi Zhaoyuan et al. measured and analyzed the spatial differentiation of new quality productive forces in China's marine economy and their multi-level cultivation pathways [6]. Regarding industrial integration and green synergy, Fu Linlin explored the construction of green financing models for emerging marine industries driven by digital transformation [7]; Li Chunlin et al. systematically identified the hierarchical structure of factors influencing maritime power construction, arguing that scientific and technological innovation plays a core driving role [8].

At the level of country studies, Chinese scholars have conducted relatively extensive investigations of major maritime powers. Zhang Yizao et al. reviewed the staged characteristics of Japan's marine economy as it shifted from scale expansion to strategic focus, summarizing its experience in strengthening the nation through marine technology [9]; Xing Wenxiu et al. analyzed the spatial distribution pattern and recent dynamics of the U.S. marine industry, noting that the United States maintains relative advantages in marine mining and biological resources [10]. Compared with the relatively rich research on countries such as the United States and Japan, systematic research on Portugal—a country with a prominent marine functional position within the EU framework and distinctive maritime characteristics—remains limited; existing studies mostly focus on its macroeconomy or China-Portugal economic and trade relations, and systematic accounts of the strategic arrangements, implementation mechanisms, and practical constraints of its marine industry digital transformation are still lacking.

Accordingly, based on Portuguese official strategy texts and EU policy documents, the study analyzes the practical logic of Portugal's marine industry digital transformation, examines its strategic framework and implementation path, summarizes the main challenges it faces, and on this basis derives implications for China, providing a cross-national reference for China's efforts to advance digital ocean development and optimize its modern marine industrial system.

2. Practical Logic of the Digital Transformation of Portugal's Marine Industry

Against the dual backdrop of tightening global ocean governance rules and the accelerating penetration of digital technologies, digital transformation is both a necessary choice for Portugal in responding to the EU's twin green and digital strategy and a key measure for overcoming the bottlenecks of its traditional marine industries and reconstructing its geoeconomic advantages.

2.1 External Constraints and Trend-Driven Pressure: Institutional Pressure from Global Ocean Governance and the EU's Twin Transition Strategy

From a global perspective, the ocean economy has entered what scholars call the "blue acceleration" stage. Research by Jouffray et al. shows that since the beginning of the twenty-first century, the intensity of human exploitation of ocean space, the speed of resource utilization, and the degree of data dependence have all grown exponentially [11]. According to the EU Blue Economy Report 2025 published by the European Commission, in 2023 the EU blue economy generated approximately €263 billion in gross value added and directly employed about 4.88 million people; its scale continues to expand, with digitalization and greening as its main directions of evolution [12]. In this context, the capacity to acquire and process marine data has increasingly become an important dimension for measuring national maritime power, making digital transformation a realistic choice for Portugal to maintain its position amid the restructuring of the global blue economy value chain. The focus of maritime competition is extending from resource possession and spatial jurisdiction to competition over data acquisition, technical standards, and rule-making capacity; major maritime states have listed marine data infrastructure as a strategic investment direction, and digital transformation thereby carries strategic significance that transcends the industrial level.

A more immediate external driver comes from EU-level institutional norms. As a member state, Portugal's ocean strategy must be integrated into the EU's macro-governance system. The European Green Deal introduced in 2019 and the EU's new approach for a sustainable blue economy released in 2021 established a strategic orientation in which the green and digital transitions proceed on parallel tracks. The EU has set emission-reduction and digitalization compliance requirements for member states' marine industries, and in the construction of European marine data and observation networks Portugal undertakes obligations to collect and share data relating to the Atlantic. Such policy requirements, transmitted from the EU to member states, have prompted Portugal to use digital means to enhance the transparency, resource-use efficiency, and intelligence of its marine economy, so as to align with the quantitative targets of the EU's Digital Decade strategy. Through the Digital Decade policy program, the EU has also set targets for 2030 in digital infrastructure, digital skills, and the digitalization of public services, on which member states must report progress regularly. For Portugal, the marine domain is both a priority arena for fulfilling its EU emission-reduction and digitalization obligations and an important direction for securing EU structural funds and recovery funding; digital transformation thus became the junction connecting EU norms with the domestic development agenda.

2.2 Internal Imperatives and Industrial Bottlenecks: Redressing the Imbalance Between a Vast Maritime Jurisdiction and Lagging Development Capacity

The principal contradiction facing Portugal's marine economic development lies in the structural imbalance between its vast maritime jurisdiction and its relatively lagging capacity for development and regulation. Portugal's exclusive economic zone covers approximately 1.7 million square kilometers; its maritime jurisdictional area is about 18 times its land area, ranking among the largest in the EU and worldwide [12]. However, the country's long-standing investment in deep-sea resource monitoring, patrol, and scientific development has been limited, and its regulatory capacity does not match the scale of its maritime space. A vast maritime area is both a resource endowment and a source of high governance costs; traditional supervision methods centered on manual patrols can hardly cover such an extensive area. Advancing digital transformation—by building a digital twin ocean and remote monitoring systems—has become an endogenous imperative for Portugal to strengthen data sovereignty over its maritime spaces and improve the effectiveness of spatial governance.

Meanwhile, Portugal's traditional advantage industries face multiple challenges. The aging of the inshore fisheries workforce has become evident, and traditional fishing operations face the dual pressures of resource depletion and ecological protection; the shipbuilding industry, against a backdrop of low-end overcapacity and intensifying international competition, has seen persistently low added value. Statistics indicate that by 2012 Portugal's share of global shipbuilding completions had fallen to about 0.002% in gross tonnage terms, and industry employment had shrunk from nearly 10,000 in the 1990s to about 3,800 in 2013 [13]. Under these circumstances, using artificial intelligence to optimize fishing routes and digital design and manufacturing technologies to enhance the customization capabilities of small and medium-sized shipyards has become an important pathway for Portugal's marine industries to improve quality and efficiency and to shift from scale expansion to value-driven development. In terms of industrial structure, Portugal's marine economy is dominated by traditional sectors such as coastal tourism, port logistics, and fisheries, with a low share of high-value-added segments; growth momentum weakened after the sovereign debt crisis, and digital transformation has accordingly been invested with expectations of reshaping industrial competitiveness and fostering new growth points.

2.3 Technological Empowerment and Strategic Opportunity: The Evolution of Digital Technologies and the Revaluation of Geoeconomic Advantages

The clustered development of digital technologies provides a technological foundation for upgrading Portugal's marine industries. The maturation of the Internet of Things, underwater communication technologies, and ocean digital twin programs has lowered the cost threshold of deep-sea resource development and scientific research activities, making large-scale, continuous marine environmental monitoring economically feasible. The ENM 2021-2030 explicitly proposes using digital tools to promote the reindustrialization of the blue economy [14], a formulation that elevates digitalization from an efficiency tool to a strategic fulcrum for industrial cultivation. Portuguese research institutions have accumulated certain technological capabilities in fields such as underwater robotics and marine sensors, providing support for the local application of relevant technologies. The evolution of these technologies has enhanced the feasibility of deep-sea research and created underlying enabling conditions for Portugal to cultivate forward-looking industries such as marine biomedicine and offshore renewable energy.

The digital revaluation of geoeconomic advantages, in turn, has opened a strategic window for Portugal. Located at the southwestern tip of the European continent, Portugal is an important node in Atlantic digital connectivity. Leveraging this position, Portugal has achieved low-latency transoceanic direct connection between Europe and Latin America through the EllaLink submarine cable [15], and has laid out the Start Campus hyperscale data center cluster in Sines, a project with a planned installed capacity of 1.2 GW and a total investment of approximately €8.5 billion, whose first facility entered operation at the end of 2024 and has attracted substantial investment from international technology companies [16]. The layout of such digital infrastructure extends Portugal's strategic depth from physical maritime space into data space, helping to aggregate transatlantic data flows and enhance its participation in and influence over the international blue economy governance system [17]. Benefiting from the landing conditions of multiple international submarine cables and relatively low energy costs, Sines is becoming an emerging data infrastructure node in Europe, where maritime locational advantages and digital infrastructure investment form a superimposed effect.

3. Strategic Framework and Implementation Path of the Digital Transformation of Portugal's Marine Industry

The strategic arrangements for the digital transformation of Portugal's marine industry can be divided into two levels: the strategic framework and the implementation path. Top-level strategic planning and the collaborative governance architecture constitute the strategic framework, addressing goal setting and organizational safeguards; digital infrastructure, data-sharing platforms, and the talent cultivation system constitute the implementation path, addressing on-the-ground support. The two interlock to form a complete closed loop from goal setting to execution.

3.1 Top-Level Strategic Planning: Centered on the National Strategy for the Sea 2021-2030

3.1.1 Policy Evolution: From Resource Orientation to Data-Driven Governance

At the beginning of the twenty-first century, Portuguese ocean policy focused mainly on the legal delimitation of maritime space—such as the extended continental shelf submission—and on the static management of traditional resources such as fisheries and oil and gas. As the “blue acceleration” trend developed, Portuguese policymakers gradually recognized that sovereign claims over physical space alone were insufficient to sustain the country’s position in the global blue value chain. In the early stage of the policy shift, the approach of empowering traditional industries with digital technologies prevailed, emphasizing the use of digital means to solve problems in specific links such as fisheries supervision and port efficiency. The ENM 2021-2030, approved in 2021, further established the “data first” principle, treating data itself as a marine resource. Around this positioning, the strategy sets out 13 priority action areas covering the blue bioeconomy, marine renewable energy, the digitalization of ports and shipping, and marine data and observation, with digital tools embedded in the action measures of each area [14]. The strategy proposes that Portugal position its Atlantic jurisdictional waters as a “large living laboratory,” deepening knowledge of marine ecosystems through multidimensional data collection across underwater, surface, and coastal domains, and using this as a collaborative space for scientific research and technological innovation at the European level, thereby shifting the governance model from passive response to proactive planning [14]. This evolution reflects Portugal’s judgment of the regional competitive landscape: states possessing real-time situational awareness of the ocean will gain greater institutional voice.

3.1.2 Core Vision and Quantitative Targets

The core vision of the strategy is to advance marine ecological protection and economic growth in coordination, with a clearly tiered quantitative system built around 10 strategic objectives, 34 specific targets, and 185 action measures [14]. By 2030, 30% of national jurisdictional waters are to be designated as marine protected areas, one third of them under strict protection; installed capacity for energy generation from ocean renewable sources is to reach at least 370 MW; national aquaculture output is to rise to 25,000 tonnes per year; employment in the blue economy is to grow by 30%; gross value added of the marine economy is to grow by 30% and account for 7% of national value added; and greenhouse gas emissions from maritime activities are to be reduced by 17% relative to 2005 [14]. These targets span ecological protection, industrial upgrading, and emission constraints, providing clear policy anchors for the digitalization of the marine industry. Compared with the previous version of the strategy, the ENM 2021-2030 elevates digitalization from an instrumental arrangement to a principled requirement, and the degree of quantification of the target system has increased markedly.

3.2 Collaborative Governance Architecture: A “Government-Industry-University-Research-Finance” Network

3.2.1 Government Coordination: The Ministry Responsible for the Sea and the Directorate-General for Maritime Policy

At the level of top-level coordination, Portugal maintained a dedicated Ministry of the Sea between 2015 and 2022, whose functions were subsequently integrated into the Ministry of Economy and the Sea, which assumes strategic planning and coordination functions in the digital transformation [18]. The ministry responsible for the sea handles the macro-planning of the national ocean strategy and, through its executive agency, the Directorate-General for Maritime Policy (DGPM), exercises whole-process management of digitalization projects from policy design and access review to implementation supervision. This relatively centralized management model helps improve policy transmission efficiency and ensures that national strategic objectives are effectively conveyed to micro-level industrial actors. Within functional lines such as maritime spatial planning, fisheries management, and maritime supervision, the application of digital tools is likewise coordinated by these institutions, helping maintain consistency of policy direction.

3.2.2 Financial Drivers: The Guiding Mechanism of the Fundo Azul (Blue Fund)

In terms of factor input, the Portuguese government established the Fundo Azul (Blue Fund), which serves to channel capital factors toward the marine domain. Unlike traditional government subsidies, the fund emphasizes the dual attributes of digitalization and greening in project evaluation, reflecting a strategic investment orientation. Through investment and financing arrangements combining government guidance funds with social capital, the fund aims to ease the financing constraints faced by marine technology start-ups in their early development stages, using public funds to share the uncertainty of early-stage R&D and guiding social capital toward marine digital technologies. In its mode of operation, the fund selects projects through open calls and competitive evaluation; supported areas cover marine monitoring technologies, blue biotechnology, sustainable fisheries, and port decarbonization, and recipients include research institutions, start-ups, and industry associations, forming a cross-actor project portfolio.

3.2.3 Cluster-Based Translation: Fórum Oceano and the Portugal Blue Digital Hub

At the micro-implementation level, Portugal adopts governance arrangements organized around industrial clusters. Fórum Oceano, the national marine cluster management body certified by multiple government departments, has more than 170 member organizations and plays a role in connecting policy orientation with market demand and promoting information sharing and collaboration in the digital transformation [19]. To promote the translation of research results into industrial application, the forum took the lead in establishing the Portugal Blue Digital Hub (PBDH), a project co-funded by the EU Recovery and Resilience Plan and EU funds [19], which unites 17 institutions in an innovation consortium that applies artificial intelligence, blockchain, and big data technologies to accelerate the dual digital and ecological transformation of blue economy SMEs and public sector entities [19]. Taking the collaboration with the blockchain technology company Yacooba Labs as an example, university research teams digitized long-accumulated marine biological sample data and jointly developed an integrated blockchain traceability and data platform, consolidating more than 2,000 cyanobacterial and microalgal strains from across Portugal together with their genomic information, thereby enabling enterprises to access biological resource data more conveniently and shortening the R&D cycle for marine biomedicine and bioremediation products [20]. The blue bioeconomy has also been incorporated into the priority areas of the national ocean strategy and received policy support through the Action Plan for a Sustainable Bioeconomy (PABS) [21]. According to data from the Hub Azul Dealroom platform cited by Fórum Oceano, as of 2023 the platform listed 47 Portuguese blue start-ups, of which eight had registered valuations totaling approximately €194 million [19]. The cluster also regularly organizes digital maturity assessments and transnational technology exchanges, incorporating dispersed innovation actors into a relatively systematic collaborative network [19]. This organizational path from nodes to network, while increasing the depth of digital penetration along the industrial chain, compensates through organizational synergy for the limitations of individual market actors' technological capabilities.

3.3 Implementation Path: Triple Support from Infrastructure, Data Platforms, and Talent Cultivation

3.3.1 Foundational Support: A Ubiquitous Marine Digital Infrastructure Network

At the level of physical interconnection, Portugal is advancing the construction of submarine communication networks that also possess environmental sensing functions. The representative project is the Atlantic CAM intelligent submarine cable system connecting mainland Portugal, the Azores, and Madeira; the Portuguese side signed the contract with Alcatel Submarine Networks in March 2024 [22]. With a total length of about 3,800 kilometers and an investment of approximately €190 million, the project's budget was re-programmed by Council of Ministers Resolution No. 183/2025 in November 2025 [23], with specialized institutions estimating the investment at about €190.4 million [24]. The system is designed with six fiber pairs and a transmission capacity about five times that of the original system, and the investment covers the construction and operation cycle from 2023 to 2051 [23][24]. Building on a conventional communication cable, the system integrates scientific monitoring and reliable communication sensor technologies; sensors deployed along the route can collect in real time parameters such as deep-sea temperature, hydrostatic pressure, earthquake and tsunami risk, and ocean climate change, turning the communication line simultaneously into a transatlantic underwater environmental monitoring platform [25]. At the level of sensing and identification, Portugal, through the coordination of the Atlantic Observatory and the Atlantic International Research Centre (AIR Centre), deploys a collaborative monitoring network composed of smart sensor buoys, underwater gliders, and autonomous unmanned vehicles; combined with satellite remote sensing and underwater Internet of Things technologies, this network achieves continuous digital monitoring of the exclusive economic zone, and edge computing is used at the front end to perform preliminary identification and early warning of events such as illegal fishing and oil spills, thereby reducing the response time and operating costs of deep-sea supervision [25]. The multi-functional reuse of such facilities improves the efficiency of public investment and provides continuous observation conditions for marine scientific research.

3.3.2 Data Platforms: A National Marine Data-Sharing System Centered on Interoperability

In terms of data governance, Portugal established the National Ocean Information System (SNIMar) in 2017, centrally integrating marine-related data resources dispersed across the navy, environmental agencies, and research institutions; in the year of its launch it opened 2,238 metadata sets and more than 6,000 historical records [26]. Following the EU's data principles of findability, accessibility, interoperability, and reusability, the platform systematically organizes and publishes marine geographic, biological, hydrological, and economic statistical data through unified metadata standards and interface specifications. Government departments have pursued open public data policies, creating conditions for market actors to use public data resources in application development and giving rise to commercial products such as smart weather navigation and blue tourism digital applications, thereby reducing the innovation costs and R&D risks of marine-related start-ups. From a governance perspective, a unified data platform reduces the resource waste caused by duplicative collection, facilitates cross-departmental data comparison and comprehensive assessment, and provides a data foundation for the monitoring and evaluation of the national ocean strategy. The sustained operation of the data platform also depends on stable maintenance investment and interdepartmental coordination mechanisms; this institutional arrangement offers a reference for other countries building similar platforms.

3.3.3 Talent Cultivation: A Blue Digital Skills Development System

In terms of human capital development, Portugal, through channels such as the PBDH, has launched blue digital skills training delivered mainly through online learning, providing customized courses in digital literacy, innovation capacity, and digital transformation skills for blue economy practitioners and related organizations [27]. This arrangement aims to narrow the skills gap between the traditional marine industry workforce and the requirements of digital transformation, providing a human capital reserve for the sustainable development of marine industries while balancing technological evolution with social participation. The training content addresses both incumbent workers and job seekers and is aligned with the job requirements of cluster enterprises in order to improve the conversion rate of training outcomes [27].

4. Challenges Faced in the Digital Transformation of Portugal's Marine Industry

4.1 External Dependence in the Funding Structure and Uncertainty in Target Implementation

The advancement of Portugal's marine digitalization projects exhibits, at the level of financing, a marked dependence on EU fiscal transfer payments, displaying an exogenously driven character. Funding for its key digital infrastructure construction and start-up incubation comes mainly from appropriations under the EU Recovery and Resilience Plan (PRR), the European Regional Development Fund, and the European Maritime, Fisheries and Aquaculture Fund. As the first country to submit a recovery plan to the EU, Portugal has planned dedicated investment of approximately €252 million in the blue economy, focused mainly on the construction of marine digital hubs [28]. The Portuguese recovery plan lists the blue economy as one of its priority investment directions, with related funds directed mainly toward port digitalization retrofits, marine monitoring networks, and the incubation of blue start-ups; public funding has thus formed a relatively concentrated input in the short term. However, against the backdrop of large inflows of external funds, the endogenous investment momentum of domestic marine-related enterprises—especially small and medium-sized enterprises in the real economy—remains insufficient; the transformation process lacks stable commercial support, most marine technology projects are still in the transition from R&D demonstration to commercialization, and technology spillover effects and self-sustaining profit mechanisms have yet to form.

This pattern reflects the structural constraints of Portugal's own capital formation mechanism. Marine digital infrastructure is capital-intensive, has long payback periods, and involves high sunk costs, while Portugal's domestic capital market is limited in size. According to OECD statistics, as of the end of 2024 Portugal had only 35 listed companies, with a combined market capitalization of approximately US$89 billion [29]; equity financing channels are markedly constrained, private capital remains cautious toward long-cycle, high-sunk-cost projects, and the room for domestic market-based investment and financing mechanisms is narrow. At the same time, a development model highly dependent on policy-based funding faces the potential impact of external cyclical changes. If the PRR funding cycle ends on schedule in 2026, or if fiscal resources are reallocated amid changes in the geopolitical situation, the innovation ecosystem supported mainly by public subsidies will face the pressure of shrinking funding sources.

The gap between target setting and implementation also warrants attention. Taking offshore wind power as an example, the 10 GW capacity figure was an auction-scale target publicly announced by the Portuguese government during 2022-2023 and was not written into the earlier version of the National Energy and Climate Plan (PNEC); both the 2023 draft revision of the plan and the final version approved in 2024 by Council of Ministers Resolution No. 149/2024 make clear that only 2 GW of offshore wind will be operational by 2030 [30]. The substantial contraction of the planned target reflects uncertainty in policy implementation in the marine renewable energy sector. Although the target adjustment makes planning more pragmatic, it also indicates that mobilizing industry through grandiose target announcements carries implementation risks, with particular impact on enterprises that arrange investment decisions on the basis of policy signals.

4.2 Uneven Distribution of Digitalization Across Industries

The digital transformation of Portugal's marine economy displays marked inter-sectoral differences: fields with low capital intensity advance slowly, while fields with high capital intensity advance relatively rapidly. On the one hand, in capital-intensive fields such as offshore wind power and large hub ports—thanks to the participation of transnational capital and the tilt of public resource allocation—technologies such as the Internet of Things, blockchain logistics tracking, and AI-assisted automated loading and unloading have been applied relatively quickly. The Port of Sines, for example, has through a relatively high degree of digitalization become one of the more efficient smart hubs on the Iberian Peninsula and the west coast of Europe [31]; port digitalization has also driven efficiency gains in associated links such as shipping logistics, warehousing, and trade, generating localized industrial agglomeration effects. On the other hand, the main body of Portugal's marine economy consists of a large number of micro, small, and medium-sized enterprises (MSMEs): more than 90% of the entities engaged in marine industries are MSMEs, and organizational forms are especially fragmented in links such as inshore artisanal fisheries, traditional aquaculture, and primary processing of marine products [32]. Such operators have limited profit margins and considerable day-to-day operating cost pressure; their capacity to invest in hardware and software upgrades, data system maintenance, and the procurement of algorithmic tools is constrained, the scale economies of digital technologies are hard to realize, and a cycle thus forms between insufficient digital investment and limited efficiency gains. This capital-constraint-based gap in technology application will widen productivity differences between large enterprises and MSMEs and place greater pressure on some labor-intensive traditional marine activities amid structural adjustment, with corresponding effects on the economic structure of traditional coastal communities. Moreover, digital infrastructure and investment are concentrated mainly in major port hubs, while the technology spillovers reaching the coastal areas where traditional fishing communities are located remain relatively limited; spatial and sectoral differences in the transformation overlap, and if such differentiation persists over the long term it will weaken the overall synergy of the marine economy.

4.3 Data Barriers, Data Rights Mechanisms, and National Security Considerations

Data are the core factor in the digital transformation of marine industries, but Portugal faces both technical and institutional obstacles in the sharing and joint development of marine data. Regarding data rights confirmation and governance mechanisms, although public platforms such as SNIMar have been established, the navy, the Portuguese Institute for Sea and Atmosphere (IPMA), port authorities, and university research institutes still lack unified data standards and interaction protocols, and interdepartmental data interconnection remains insufficient [33]. Market-based pricing mechanisms for marine data as a factor of production and the definition of rights attribution are still at an exploratory stage; on the basis of their remit boundaries or expectations of potential value, data-holding entities tend to manage high-quality data as internal resources, and some raw data fail to circulate effectively and to be transformed into resources usable for industrial innovation. Under lagging institutional supply, data sharing depends more on case-by-case negotiation, transaction costs are high, and the overall allocation efficiency of marine data as a factor of production is suppressed.

At the external security level, the process of marine digitalization has become entangled with global strategic rivalry. As transatlantic submarine cables and deep-sea infrastructure equipped with scientific sensors advance, the node status of Portugal's relevant maritime areas in the global data network is rising, while the real-time hydrological, geological, and acoustic information collected by submarine infrastructure involves sensitive content bearing national security attributes, such as seabed environmental conditions and resource distribution [34]. In an environment of tightening compliance requirements under the EU General Data Protection Regulation (GDPR) and data sovereignty rules, Portugal must, on the one hand, bring in capital and technology from outside the EU to participate in large-scale marine digital infrastructure construction and, on the other hand, prudently manage cross-border flows of marine data involving security domains, thereby increasing the compliance costs and policy coordination difficulties of transnational digital cooperation. The absence of data-rights rules has also dampened enterprises' enthusiasm for investing in data collection and processing. In the long run, whether a stable and predictable institutional arrangement can be established between openness to investment and security review will directly affect the extent to which Portugal's positioning as an Atlantic digital hub can be realized.

4.4 Slow Transition of the Traditional Workforce and the Outflow of High-End Digital Talent

The human capital constraint on Portugal's digital transformation has a two-layer structure: the digital skills transition of the traditional marine workforce is slow, while high-end composite digital talent continues to flow out. At the level of the traditional workforce, practitioners in Portugal's fisheries and traditional ship repair and building industries are on average relatively old, young workers' willingness to enter traditional marine industries remains persistently low, and the relevant industries face pronounced pressure of workforce succession [35]. The older generation of practitioners, long reliant on experiential knowledge, faces high learning costs in adapting to new technologies such as artificial intelligence and remote automated control; bringing digital skills training down to coastal fishing villages and shipyards is difficult to implement, and the mismatch between training supply and frontline demand limits the actual conversion efficiency of digital skills policy at the grassroots, leaving part of the traditional workforce unable to share in the gains of digital transformation. Although Portugal has introduced policy instruments such as blue digital skills training, a gap remains between policy coverage and actual industrial demand.

At the level of high-end talent, Portugal's higher education system has a certain capacity to train specialists in marine engineering, underwater robotics, and marine data, but the outcomes of this training face persistent outflow pressure. According to estimates by the BRADRAMO special research project based on the OECD International Migration Database, Portugal's highly skilled emigration rate reached 12.9% in 2010-2011, far above the average of 5.3% for European OECD countries, making it one of the European countries with the most severe outflows of highly skilled talent [36]; related survey research likewise shows that highly educated Portuguese emigrants mostly flow to northwestern European countries offering better pay and career development space, and that 36.1% of surveyed highly educated emigrants were unemployed when leaving Portugal, a share that fell to 3.8% after moving elsewhere in Europe, reflecting the domestic labor market's insufficient capacity to absorb highly skilled positions [37]. Under conditions in which domestic salary levels and corporate tax burdens are relatively uncompetitive, the long-term shortage of high-end algorithm engineers, marine data analysts, and composite project management talent keeps local marine-related enterprises largely in the application segment of the digital technology value chain, raising the threshold for Portugal's marine industry to climb toward the high-end links of the global digital value chain. Talent outflow and population aging overlap, giving the skills gap of the digital transformation an intergenerational character that short-term training policies alone can hardly alleviate fundamentally.

5. Implications of Portugal's Digital Transformation Experience for China

The analysis above indicates that Portugal's marine industry digital transformation has both accumulated experience worth drawing upon and exposed risks that require guarding against. Its implications for China can be developed along two lines. The first is drawing on experience, corresponding mainly to the positive practices in the strategic framework and implementation path described in Section 3, namely top-level design centered on data as a factor of production and infrastructure construction based on multi-functional reuse; the second is risk prevention, corresponding to the four categories of challenges described in Section 4, among which dependence on external funding and uneven industrial digitalization can be grouped under the issues of coordination mechanisms and balanced transformation, while data barriers and talent loss jointly point to the security and sustainability of the digital ocean ecosystem. Accordingly, the implications for China can be summarized in the following three respects.

5.1 Strengthening Top-Level Design and Infrastructure Support and Establishing the Strategic Status of Marine Data as a Factor of Production

For China, marine data should be incorporated as a new factor of production into the core concept of national marine economic planning. China's marine economy has already reached a considerable scale: in 2024 gross ocean product surpassed 10 trillion yuan for the first time, accounting for 7.8% of GDP; value added in emerging marine industries grew by 7.2%; and applications such as fishery large models, AI-based fishing condition forecasting, and digital ship management systems accelerated their deployment [2]. National planning has likewise made arrangements for the digital transformation of the marine economy [1]. On this basis, the strategic positioning of marine data as a factor of production can be further elevated; institutional arrangements for the collection, rights confirmation, circulation, and asset-based operation of marine data can be improved; the deep mining of marine data can be encouraged; and China's institutional voice in deep-sea development and the global blue value chain can be strengthened. In planning formulation, dedicated content on the development and utilization of marine data resources can be established, with clear public data opening catalogs and updating mechanisms, so that the supply of data factors and industrial demand form a stable connection. At the same time, the marine data standards system should be improved, promoting the unification of observation equipment, data formats, and interface specifications and laying a technical foundation for cross-regional and cross-departmental data aggregation. China's marine economic statistics and monitoring system is already relatively complete; the priority of the next stage lies in the deep development of data rather than the simple expansion of collection scale.

At the same time, a ubiquitous and intelligent marine digital infrastructure network should be built in a coordinated manner. China would do well to draw on the idea of reusing communication facilities for scientific monitoring functions, breaking down barriers between communication facilities and marine research facilities; relying on the BeiDou Navigation Satellite System, marine remote sensing satellites, and 5G and 6G networks, in coordination with deep-sea intelligent sensor networks and submarine cable systems, it should accelerate the construction of an integrated space-air-ground-sea comprehensive marine sensing network, promote the deep integration of physical communication, hydro-meteorological monitoring, and industrial operation data, and provide hardware support for building a digital twin ocean. In facility layout, marine observation interfaces can also be reserved in coordination with major coastal projects, promoting one-time construction and multiple reuse and improving the overall benefits of public investment. On this basis, the conversion of marine sensing data into industry applications such as weather forecasting, shipping logistics, and fishery production should be promoted, forming a closed loop of data collection and value realization.

5.2 Optimizing the "Government-Industry-University-Research-Finance" Coordination Mechanism and Guarding Against Polarization in Industrial Digitalization

China should leverage the advantages of its super-large-scale market and the new system for mobilizing resources nationwide (新型举国体制) to build a marine digital industry ecosystem in which leading enterprises serve as chain owners and "government, industry, universities, research institutes, and finance" coordinate with one another. On the one hand, drawing on the operation of national-level marine clusters, national and regional collaborative innovation platforms for marine industry digitalization can be established to connect research institutions' data resources with enterprises' development needs and reduce the costs of cross-domain collaboration; on the other hand, financial mechanisms through which social capital, industrial funds, and venture capital support marine digital technology should be improved, using instruments such as blue bonds to enhance the innovation investment capacity and trial-and-error space of domestic marine-related enterprises and avoiding excessive dependence of the digitalization process on any single source of policy-based funding. In cluster construction, the supply responsibilities for public goods such as data, platforms, and standards should also be clarified, so that SMEs can share the cluster's innovation resources at relatively low cost; and through measures such as first-set (first-unit) equipment policies, government procurement, and demonstration applications, early markets can be provided for marine digital technologies, shortening the cycle from technological maturity to scaled application. Financial support should also match the stage of industrial development, emphasizing risk sharing for early-stage projects and scaled financing for mature projects.

At the same time, breakthroughs in high and new technologies should be coordinated with the inclusive transformation of traditional industries. China has a large population of traditional marine industries; while advancing frontier transformations such as the digital-intelligent upgrading of key ports and deep-sea intelligent aquaculture, attention must be paid to the transformation capacity of micro, small, and medium-sized marine-related enterprises and subsistence fishers. The government can introduce inclusive digital tool support policies for micro, small, and medium-sized marine-related entities, guiding the development of low-cost, modular, and easy-to-operate public cloud service platforms and digital solutions, lowering the threshold of technology application, preventing the continuous widening of productivity gaps within the marine industry, and extending the dividends of digitalization to traditional industrial groups in coastal areas. At the regional level, differentiated pilot programs can be carried out relying on coastal city clusters and marine economic development demonstration zones, forming replicable and scalable digital transformation solutions for traditional industries.

5.3 Breaking Down Data Barriers and Talent Mismatches to Consolidate the Security and Talent Foundations of the Marine Digital Economy

China should accelerate the construction of a national-level market for marine data as a factor of production and formulate unified standards for the classification and grading of marine data together with rules for rights confirmation and pricing. Internally, data barriers between the military and civilian spheres and among marine-related departments should be broken down, and mechanisms for the opening and authorized operation of desensitized marine public data should be established to improve the allocation efficiency of data factors; externally, on the premise of safeguarding marine data security and preventing the leakage of sensitive spatial geographic information, and relying on the 21st-Century Maritime Silk Road, the docking of digital rules and cooperation on cross-border flows of marine-related data with partner countries should be steadily advanced. Portugal was among the first EU member states to establish a blue partnership with China; the two sides can deepen alignment in areas such as smart ports, marine data governance, and blue science and technology, making the China-Portugal blue partnership a practical vehicle for marine digital cooperation. For example, relying on bilateral marine science and technology cooperation mechanisms, the two sides can carry out exchanges of marine observation data and exchanges among blue start-ups, combining Portugal’s node position in Atlantic waters with China’s capabilities in digital technology and equipment manufacturing to form a complementary cooperation pattern. At the multilateral level, China can also actively participate in the formulation of rules on the protection of international submarine cables and standards for marine data exchange, and explore the establishment of a security assessment mechanism for cross-border flows of marine data, expanding the scope of international cooperation under controllable risks and enhancing its institutional influence in global digital ocean governance.

In terms of talent, China also needs to guard proactively against the structural contradiction between the aging of the traditional marine workforce and the shortage of digital talent. On the one hand, drawing on the operating model of online skills platforms, blue digital skills training can be incorporated into coastal vocational education and re-employment programs, providing digital literacy popularization and job-transition support for traditional fishers and port workers; on the other hand, for composite talent in key fields such as marine artificial intelligence and marine big data algorithms, research evaluation and compensation incentive systems should be improved, and internationally competitive career development pathways should be provided relying on key laboratories and marine-related new areas, reducing the risk of high-end talent loss and consolidating the talent foundation for digital ocean development. At the same time, through interdisciplinary training at marine-related universities and university-enterprise joint projects, the supply of composite talent possessing both marine expertise and digital technology capabilities can be expanded. Talent policy should also be dynamically matched with industrial demand, using industry talent monitoring and early warning mechanisms to identify skills gaps in key fields in a timely manner.

Conclusion

Portugal has advanced the digital transformation of its marine industry on the top-level basis of the ENM 2021-2030, establishing a “data first” logic; building a “government-industry-university-research-finance” collaborative network in which the ministry responsible for the sea provides overall coordination, the Fundo Azul (Blue Fund) provides financial impetus, and clusters translate research into application; and pursuing an implementation path supported by infrastructure, data platforms, and talent cultivation, thereby promoting the application of digital technologies in areas such as smart ports, marine data governance, and marine renewable energy.

The transformation faces multiple constraints: dependence on EU transfer payments amid a limited domestic capital market; uncertainty in target implementation reflected in the contraction of the offshore wind target from 10 GW to 2 GW; the uneven penetration of digital technologies across industries of differing capital intensity; restrictions on data flows arising from the absence of data rights confirmation and cross-border security considerations; and the human capital constraints of a slowly transitioning traditional workforce and the outflow of high-end talent.

For China, it is advisable to draw on Portugal's experience in using data as a factor of production to guide top-level design and in building marine infrastructure through multi-functional reuse; to leverage the advantages of the super-large-scale market and the new system for mobilizing resources nationwide; to guard against the risks of funding externalization, industrial polarization, and talent loss; and to expand marine digital cooperation by relying on the China-Portugal blue partnership. The study is limited to a single country case, and some of its judgments rely on official texts; future research may introduce multi-country comparisons and micro-level evidence.

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