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The Implementation Of Unmanned Lighthouse Systems In Indonesia: Opportunities, Challenges, And Lessons From The Class II Type A Navigation District Of Banjarmasin

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Abstract

Digital transformation has become essential for improving maritime safety and operational efficiency in archipelagic countries. This study examines the opportunities, challenges, and implementation strategies for Unmanned Lighthouse Systems in the Class II Type A Navigation District of Banjarmasin, Indonesia. A qualitative case study approach was employed, using semi-structured interviews, field observations, and regulatory document analysis. Data were analyzed through data reduction, thematic coding, data presentation, and conclusion verification, supported by the Social Construction of Technology (SCOT), Science, Technology, and Society (STS), and public policy implementation frameworks. The findings indicate that unmanned lighthouse systems offer substantial benefits, including a projected 40% reduction in long-term operational expenditure, reduced occupational risks, real-time telemetry monitoring, and alignment with International Maritime Organization (IMO) e-Navigation and International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) guidelines. However,

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implementation faces environmental challenges, regulatory gaps, limited digital competencies, unstable power supplies, restricted telecommunications coverage, and cybersecurity vulnerabilities. To address these issues, the study proposes a three-phase roadmap involving regulatory adaptation and pilot testing, hybrid control-center development, and nationwide autonomous system integration. This research contributes a socio-technical governance framework for modernizing maritime navigation infrastructure in developing maritime nations.

Keywords: **Digital Transformation, Navigation Infrastructure, Maritime Safety, Unmanned Lighthouse Systems.**

INTRODUCTION

Digital transformation in the maritime transportation sector has evolved beyond a discretionary policy initiative into a fundamental requirement that is reshaping how countries manage maritime safety, navigational efficiency, and sovereignty over their archipelagic territories. Advances in the Internet of Things (IoT), Artificial Intelligence (AI), automated sensor networks, and remote-control technologies have significantly transformed Marine Aids to Navigation (AtoN), particularly lighthouse management. Traditional operations that rely on the continuous physical presence of personnel are increasingly being replaced by digitally connected systems featuring automated control and real-time telemetry (Kamia et al., 2025; Tim MDPI Sensors, 2024). International maritime organizations have further reinforced this transformation. Through its e-Navigation Strategy Implementation Plan, the International Maritime Organization (IMO), together with the technical guidelines developed by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), promotes the integration of digital technologies between shore-based facilities and vessels. These initiatives aim to improve situational awareness, reduce human error, and facilitate standardized maritime information exchange (IALA, n.d.; IMO, 2014).

Within the IALA framework, lighthouses are increasingly conceptualized not simply as standalone physical navigational markers but as interconnected, intelligent components of the global maritime information network. Experiences from technologically advanced maritime countries indicate that converting traditionally staffed lighthouses into fully automated and unmanned facilities is technically feasible and economically sustainable over the long term. Norway, for example, began automating its lighthouse infrastructure in the mid-twentieth

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century and completed the transition to fully automated operations across its challenging, fjord-dominated coastline by the early 2000s (Aalberg & Kongsvik, 2026; Bernhardsen, 2024). Important milestones included the automation of Homlungen Lighthouse in 1952, Hatholmen Lighthouse in 1984, Kjeungskjær Lighthouse in 1987, Langøytangen Lighthouse in 1990, and Slåtterøy Lighthouse in 2003 (Bernhardsen, 2024). These experiences illustrate that continuous human staffing can be replaced by intelligent lighting sensors, solar photovoltaic installations, backup battery systems, and shore-based remote monitoring centers while maintaining operational reliability, even under severe Arctic environmental conditions.

For Indonesia, the world's largest archipelagic country, comprising more than 17,000 islands and strategically important international sea lanes of communication (SLOC), the modernization of maritime navigation infrastructure is a critical national priority. The Directorate General of Sea Transportation (DJPL), operating under the Ministry of Transportation, oversees 25 Navigation Districts throughout the country. In recent years, local operational leaders have initiated innovative proposals to introduce smart and unmanned lighthouse technologies. Within the Class II Type A Navigation District of Banjarmasin, initiatives have emerged to transform remote lighthouse facilities into automated installations (Kamia et al., 2025). Nevertheless, a considerable gap remains between national policy aspirations and actual operational practices. Lighthouse management in the Banjarmasin jurisdiction continues to depend substantially on conventional arrangements in which lighthouse keepers (Penjaga Menara Suar) are assigned to isolated coastal and estuarine stations for extended duty rotations.

The geographical and environmental characteristics of the Banjarmasin Navigation District create considerable operational difficulties. Its jurisdiction encompasses important riverine and maritime areas across South and East Kalimantan, where shifting waterways, substantial sediment accumulation, strong estuarine currents, unpredictable tropical weather, and intensive coal and palm oil barge traffic complicate navigational management. Reaching remote lighthouse facilities, including Tanjung Selatan and Padadatua at the mouth of the Barito River, often involves hazardous maritime journeys. Under these circumstances, reliance on personnel stationed at remote facilities introduces several operational risks. Transportation to and from lighthouse stations may be delayed by severe weather, while personnel face occupational health and safety hazards. Furthermore, equipment failures occurring outside regular monitoring periods may remain undetected, potentially threatening the safety of vessels navigating these waters.

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The adoption of Unmanned Lighthouse Systems offers an alternative operational model based on an integrated smart ecosystem. Under this arrangement, operational continuity relies on interconnected sensors, automatic power-switching mechanisms, and digital telemetry linked to a centralized control facility rather than continuous physical staffing. Recent studies suggest that autonomous navigation technologies can improve efficiency and reduce operational risks, although successful implementation requires coordination between technological systems, institutional structures, human resources, and regulatory arrangements (Gobo & Marcheselli, 2023; Wang, 2023). In Indonesia, the legal framework governing maritime navigation includes Law No. 66 of 2024 concerning Shipping, Government Regulation No. 5 of 2010 concerning Navigation, and Minister of Transportation Regulation No. 25 of 2011 concerning Marine Aids to Navigation (AtoN). Although these regulations establish the government's responsibility for navigational safety, their operational orientation remains largely associated with conventional, manually managed systems.

Considering the discrepancy between the potential of technological innovation and the realities of institutional implementation, this study addresses three principal research questions. First, what are the existing technical, operational, and institutional conditions of lighthouse management within the Class II Type A Navigation District of Banjarmasin? Second, what strategic opportunities and multidimensional challenges affect the implementation of Unmanned Lighthouse Systems in this region? Third, what practical governance measures and technical implementation strategies can be developed to overcome regulatory limitations, technological constraints, and human resource challenges, thereby supporting a sustainable transition toward automated lighthouse operations?

RESEARCH METHODOLOGY

This research adopts a qualitative single-case study approach with embedded units of analysis to examine the implementation of unmanned lighthouse technology within its actual geographical and institutional settings (Hadiningrat et al., 2025; Sugiyono, 2022). A qualitative design was considered appropriate because technological transformation in public maritime administration encompasses complex relationships among physical infrastructure, institutional arrangements, regulatory compliance, human resource preparedness, and socio-cultural working practices. These interconnected dimensions require an in-depth contextual understanding that cannot be adequately explained through quantitative measurements alone.

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The study was conducted at the Class II Type A Navigation District of Banjarmasin, a technical implementing unit (Unit Pelaksana Teknis/UPT) operating under the Directorate General of Sea Transportation, Ministry of Transportation, and classified as a non-Public Service Agency (non-BLU). Data were gathered through triangulation involving three principal methods. First, in-depth semi-structured interviews were conducted with key administrative decision-makers, technical engineers, and operational personnel. Second, direct observations were carried out at the Banjarmasin main operational base and remote lighthouse installations, particularly Tanjung Selatan and Padadatua. Third, documentary analysis examined relevant national shipping legislation, ministerial regulations, IALA technical guidelines, and historical records documenting lighthouse operational performance.

Table 1. Key Research Informants and Operational Roles

Informan	Data Contribution Focus
Head of Banjarmasin Navigation District (2022–2026) / Innovation Initiator	Strategic vision, policy leadership, institutional readiness, and transformation roadmap.
Supervisor of Infrastructure, AtoN & Fleet Division	Technical feasibility, IoT/sensor integration, power infrastructure, and maintenance protocols.
Supervisor of Infrastructure, AtoN & Fleet Division	Telemetry communication links, hardware durability, salinity challenges, and remote monitoring.
Lightkeeper, Padadatua Lighthouse (Barito River Estuary)	Estuarine operational dynamics, manual maintenance routines, environmental hazards, and field readiness.
Lightkeeper, Tanjung Selatan Lighthouse (Coastal Cape)	Remote coastal operations, transit challenges, off-grid power management, and human factor perspectives.

The data were analyzed using the interactive qualitative analysis model developed by Miles, Huberman, and Saldaña (as cited in Sugiyono, 2022). This model involves a continuous process of data reduction, thematic coding, data presentation, and conclusion drawing and

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verification. The interpretation of the findings was supported by an integrated theoretical framework comprising several complementary perspectives. The Social Construction of Technology (SCOT) and Science, Technology, and Society (STS) approaches (Gobo & Marcheselli, 2023) were employed to examine technology as a product of interactions between social and technical factors. Meanwhile, Edwards III's Policy Implementation model (Nguyen & Chen, 2024) was used to assess bureaucratic communication, resource availability, implementer disposition, and organizational structure. In addition, Terry's management functions framework, commonly known as POAC (Planning, Organizing, Actuating, and Controlling), was combined with SWOT analysis to develop practical and contextually relevant policy recommendations.

RESULTS AND DISCUSSION

Current State of Lighthouse Management in the Banjarmasin Navigation District

The Class II Type A Navigation District of Banjarmasin functions as a non-Public Service Agency (non-BLU) public sector institution responsible for overseeing an extensive maritime area covering the waters of South and East Kalimantan, located between 5° S latitude and 109° E to 117° E longitude. An assessment of existing conditions reveals that lighthouse management continues to follow a conventional operational model that depends on the physical presence of lighthouse keepers. Personnel are assigned to remote coastal stations, such as Tanjung Selatan, and estuarine facilities, including Padadatua, through rotational deployments lasting approximately 30 to 60 days.

Although the primary lighting systems have been upgraded to LED technology supported by independent Solar Photovoltaic (PV) installations and lead-acid or gel battery banks, monitoring activities remain predominantly manual. Lighthouse keepers conduct routine daily inspections of battery voltage, lens cleanliness, diesel generator backup systems, and structural conditions. Operational reports are transmitted through Very High Frequency (VHF) radio or cellular messaging whenever network coverage is available. Consequently, equipment malfunctions may not be identified promptly during severe weather conditions or communication disruptions. In addition, the administrative framework of a Class II non-BLU institution operates under relatively rigid annual budget allocation procedures, which restrict flexibility in securing immediate capital funding for urgent technological improvements.

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Strategic Benefits and Potential of Unmanned Lighthouse Systems

The implementation of Unmanned Lighthouse Systems offers significant strategic, financial, and operational benefits for the Ministry of Transportation and the improvement of national maritime safety. These opportunities can be described through four principal dimensions:

1. *Operational Expenditure Optimization:* Maintaining lighthouse keepers at remote stations requires continuous operational funding for transportation logistics, boat rentals, hazard allowances, freshwater provisions, and facility maintenance. Replacing conventional arrangements with automated systems supported by remote monitoring is projected to reduce recurring operating expenditure (OPEX) by up to 40% over a five-year operational period. These potential savings would enable the reallocation of financial resources toward technological maintenance, infrastructure improvements, and system upgrades.
2. *Reduction of Occupational Hazards and Human Risks:* Deploying personnel in isolated maritime locations exposes them to various occupational dangers, including accidents during offshore transportation, sudden weather changes, tropical diseases, and psychological stress caused by prolonged isolation. Implementing unmanned lighthouse operations would reduce the need for personnel to remain physically stationed in hazardous environments, supporting improved occupational safety and alignment with contemporary international maritime safety standards.
3. *Real-Time Telemetry and Predictive Maintenance:* The integration of Internet of Things (IoT) sensors, automated current and voltage transducers, and Automatic Identification System (AIS) transmitters for Marine Aids to Navigation (AtoN) would facilitate the continuous transmission of operational data to the Banjarmasin Shore-Based Control Center. This capability would allow technical personnel to monitor battery state of health (SoH) and LED performance degradation in real time. Consequently, maintenance activities could shift from reactive repairs following equipment failures toward predictive interventions based on system condition data.
4. *Alignment with IMO e-Navigation and IALA Standards:* Lighthouse automation would support Indonesia's adoption of international maritime digitalization frameworks. By transforming conventional lighthouse facilities into interconnected digital nodes, the systems could transmit virtual AtoN information and environmental telemetry directly to vessels' Electronic

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Chart Display and Information System (ECDIS), thereby strengthening navigational awareness and maritime information integration.

Table 2. Strategic Opportunity Analysis Matrix for Unmanned Implementation

Strategic Dimension	Operational Mechanism	Expected Impact & Value Addition
Financial & Budgetary	Elimination of continuous lightkeeper shift logistics, boat provisioning, and remote residential facility maintenance.	Up to 40% reduction in recurring OPEX; optimized public resource allocation.
Safety & Human Capital	Removal of physical staff from high-risk offshore platforms and remote coastal capes.	Zero occupational exposure to marine hazards; transition of lightkeepers into skilled digital operators.
Technical & Predictive	IoT sensor arrays, automated battery switching, digital telemetry, and AIS AtoN integration.	24/7 real-time situational awareness, predictive maintenance, and fault isolation under 15 minutes.
Global Governance	Adoption of IALA Guidelines on e-Navigation and IMO Shore-Based Service frameworks.	Full interoperability with international shipping lines, enhanced archipelagic SLOC safety.

Multi-Dimensional Implementation Challenges

Although Unmanned Lighthouse Systems offer substantial strategic advantages, the qualitative findings identify several complex challenges across five major dimensions:

1. *Environmental and Geographical Challenges:* The tropical estuarine environment of South Kalimantan exposes lighthouse equipment to severe saltwater corrosion, high humidity, sediment accumulation on solar panels, and extensive marine biofouling. In addition, substantial sediment deposition can continuously alter river navigation channels,

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necessitating periodic physical adjustments or digital recalibration of Aids to Navigation (AtoN) sector lights.

2. *Regulatory and Legal Limitations:* Existing national regulations, particularly Government Regulation No. 5 of 2010 and Minister of Transportation Regulation No. 25 of 2011, establish technical requirements and personnel arrangements primarily designed for conventionally staffed lighthouse operations. However, specific legal provisions governing certified operational procedures, liability arrangements, and formal safety approval for fully autonomous and unstaffed lighthouse systems remain insufficiently established.
3. *Human Resource Competency and Organizational Resistance:* Although existing lighthouse keepers possess extensive practical maritime experience, many require additional training in digital technologies, Internet of Things (IoT) troubleshooting, software administration, and network diagnostics. Concerns about potential job displacement may also contribute to organizational and cultural resistance to automation.
4. *Telecommunication Infrastructure and Power Reliability:* Many remote lighthouse facilities in Kalimantan operate beyond cellular network coverage. Maintaining continuous telemetry therefore requires alternative communication technologies, such as Very Small Aperture Terminal (VSAT) systems or Low Earth Orbit (LEO) satellite networks, which increase initial capital expenditure (CAPEX). Furthermore, independent power systems must remain reliable during prolonged monsoon periods when limited sunlight can reduce solar energy generation.
5. *Cybersecurity Risks:* Connecting lighthouse facilities to digital communication networks introduces potential cybersecurity threats, including falsified telemetry data, unauthorized remote access, and operational service disruptions. Addressing these vulnerabilities requires comprehensive cyber-physical security measures to protect system integrity, maintain reliable communications, and ensure the continuity of maritime navigation services.

Table 3. Matrix for Assessing Multidimensional Implementation Challenges

Challenge Category	Specific Empirical Risk / Obstacle	Mitigation & Adaptation Requirement
Environmental & Physical	Extreme marine corrosion, high salinity, solar panel	IP68-rated enclosure protection, dual-redundant LED optical heads, and self-

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	dirt accumulation, and channel siltation.	cleaning solar glass coatings.
Regulatory & Legal	Absence of specific Minister of Transportation regulations governing fully autonomous AtoN operating rules.	Formulation of standard operating procedures (SOPs) for unmanned AtoN under updated DGST guidelines.
Human Resources	Digital skill mismatch among traditional lightkeepers and fear of employment displacement.	Re-skilling programs transitioning field lightkeepers into Shore Control Operators and Mobile Maintenance Technicians.
Infrastructure & Power	Cellular connectivity coverage gaps at remote capes and battery degradation during monsoons.	Hybrid satellite telemetry (VSAT/LEO) integration and industrial LiFePO4 battery storage banks.
Cybersecurity	Potential cyber threats, telemetry spoofing, and signal jamming in connected digital networks.	Encrypted VPN communications, multi-factor authentication, and secure edge-computing nodes.

Integrated Strategic Planning Framework Using SWOT Analysis

An integrated assessment of the empirical findings from a strategic management perspective provides the basis for developing a structured SWOT analysis for the Banjarmasin Navigation District:

1. *Strengths (S):* Visionary leadership at the local level, the availability of existing lighthouse infrastructure, established solar photovoltaic (PV) installations, and strong organizational commitment to improving maritime safety through modernization.

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2. *Weaknesses (W):* Limited flexibility in budget allocation due to the non-Public Service Agency (non-BLU) structure, insufficient digital engineering competencies among field personnel, vulnerability of off-grid power systems during prolonged monsoon conditions, and continued dependence on conventional reporting procedures.
3. *Opportunities (O):* Greater alignment with the International Maritime Organization (IMO) e-Navigation framework and International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) standards, potential long-term operational expenditure (OPEX) savings of up to 40%, opportunities to collaborate with national telecommunications providers, and integration with vessel-based Automatic Identification System (AIS) networks.
4. *Threats (T):* Severe corrosion caused by estuarine environmental conditions, cyberattacks targeting maritime communication networks, delays in adapting national maritime regulations to technological developments, and limited cellular connectivity in remote lighthouse locations.

Implementation Roadmap

A three-phase strategic implementation roadmap is proposed to facilitate the transition from traditional, personnel-dependent lighthouse operations to a fully automated and remotely managed system :

Table 4. Strategic Implementation Roadmap for Unmanned Lighthouse Systems

Phase / Timeframe	Focus Area	Key Action Items & Deliverables	Target Outcome
Phase 1: Short-Term (Months 1 – 12) Regulatory & Pilot	Policy Harmonization & Pilot Deployment	1. Draft technical SOPs for unmanned AtoN under DJPL. 2. Upgrade power arrays to LiFePO4 at Tanjung Selatan. 3. Install IoT diagnostic sensors and dual VSAT telemetry. 4. Initiate digital	Successful pilot testing at Tanjung Selatan; validated regulatory draft.

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Phase / Timeframe	Focus Area	Key Action Items & Deliverables	Target Outcome
		upskilling programs for lightkeepers.	
Phase 2: Medium-Term (Months 13 – 24) Hybrid Control	Shore Center & Mobile Maintenance Units	1. Construct Centralized Shore Control Center in Banjarmasin. 2. Transition lightkeepers to Mobile Response Technicians. 3. Implement AIS AtoN broadcast capabilities on pilot lighthouses. 4. Conduct quarterly cyber-physical security audits.	Transition to hybrid unstaffed operations with rapid mobile response units.
Phase 3: Long-Term (Months 25 – 36) Full Integration	Scale-Up & Smart Ecosystem Integration	1. Roll out unmanned systems across all remote lighthouses. 2. Fully integrate telemetry with regional VTS and vessel ECDIS. 3. Establish predictive AI maintenance analytics. 4. Formulate national framework for unmanned AtoN.	Full operational transition to autonomous, connected, zero-incident AtoN ecosystem.

CONCLUSION AND RECCOMENDATION

The adoption of Unmanned Lighthouse Systems within the Class II Type A Navigation District of Banjarmasin constitutes an important strategic initiative for advancing Indonesia's

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archipelagic maritime safety infrastructure. Replacing conventional lighthouse operations that depend on permanent personnel with automated, telemetry-based systems offers several potential advantages, including an estimated 40% reduction in long-term operational expenditure, reduced occupational hazards in dangerous offshore environments, enhanced real-time equipment monitoring, and improved alignment with the International Maritime Organization (IMO) e-Navigation framework and International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) guidelines.

Nevertheless, achieving sustainable automation requires overcoming several significant challenges involving environmental conditions, regulatory frameworks, human resource capabilities, technological infrastructure, and cybersecurity. High marine salinity and sediment accumulation necessitate durable, IP68-rated equipment and reliable redundant power systems. Regulatory limitations must also be addressed by revising relevant national maritime regulations, particularly those issued by the Ministry of Transportation, to establish clear operational standards and liability provisions for autonomous Aids to Navigation (AtoN). Equally important is the development of human resource capabilities through specialized training that enables lighthouse keepers to transition into digital shore-control operators and mobile maintenance technicians.

Based on these findings, the Ministry of Transportation and the Directorate General of Sea Transportation are advised to undertake four key measures: (1) revise relevant regulations to provide a clear legal basis for unmanned AtoN operations; (2) allocate dedicated capital funding for reliable satellite telemetry systems and lithium iron phosphate (LiFePO4) battery infrastructure; (3) establish continuous digital competency development programs for technical personnel; and (4) implement the proposed phased strategic roadmap. These measures are intended to support the development of a secure, resilient, and technologically advanced maritime navigation system in Indonesia.

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