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Lighthouse Modernization through Unmanned Systems: Advancing Maritime Navigational Safety

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Abstract. *Lighthouses are crucial part of Aids to Navigation, playing a vital role in ensuring maritime safety in Indonesian waters. Currently, lighthouse operations still rely on human resources, Lighthouse Keepers and Technicians, who are stationed in outposts and face various operational challenges. This condition necessitates the modernization of lighthouse management systems to enhance efficiency and adaptability in maritime safety challenges. This study explores the concept of an unmanned system as an optimal solution for lighthouse operations by leveraging technologies such as satellite-based monitoring applications, drones, and hazard detection radar. Through the implementation of this system, lighthouses can be managed remotely without the need for continuous on-site personnel presence. The proposed operational model not only improves the efficiency of lighthouse monitoring and maintenance but also minimizes safety risks for field personnel. This idea was first introduced by Hendaviny Kartomo, SE, M.Kom, a famous marine transportation professional who is the Head of Distrik Navigasi Tipe A Kelas II Banjarmasin. The notion has been presented at several internal maritime transportation forum. With this modernization, it is expected that maritime navigation safety and efficiency in Indonesia will be significantly enhanced.*

Keywords: *Lighthouse, Maritime Navigation Safety, Unmanning System*

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INTRODUCTION

Indonesia, as the largest archipelagic nation in the world, encompasses vast and complex maritime territories. To ensure the safety and security of maritime navigation, the government has constructed and currently operates 285 lighthouses, managed by 25 Navigation District Offices strategically located across the archipelago.

Lighthouses serve as critical Marine Navigational Aids (MNA) that support maritime connectivity. However, their operation still heavily relies on human personnel, including keepers and technicians, who are often stationed in remote and isolated areas. The deployment of personnel in such locations poses numerous challenges, including limited accessibility, extreme weather conditions, and inadequate supporting infrastructure. These factors can negatively impact the overall effectiveness and efficiency of lighthouse management, as well as the safety of the personnel involved.

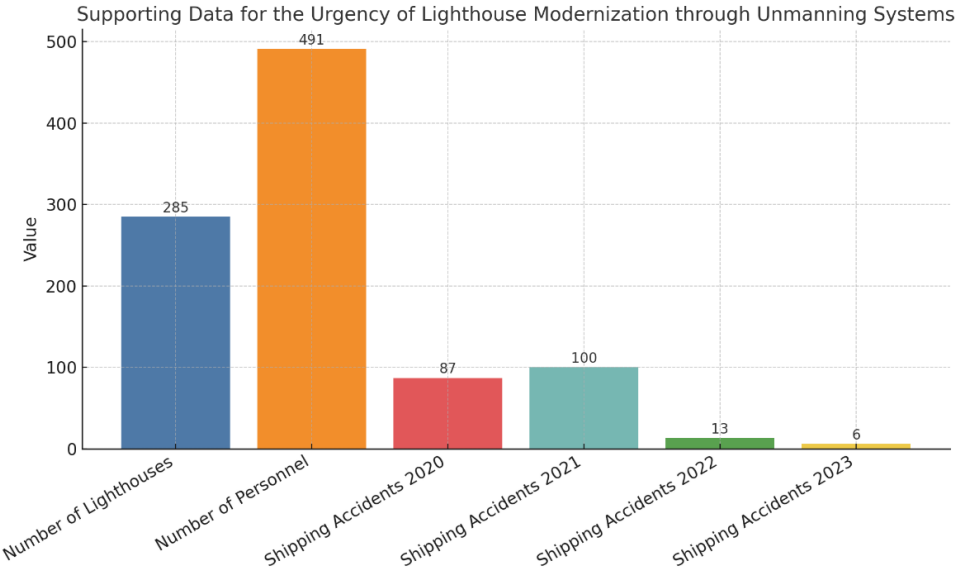
Several developed countries have adopted unmanning technologies in lighthouse operations, allowing remote operation and monitoring without the physical presence of personnel on-site. These innovations often incorporate satellite-based monitoring systems, drones, and radar technologies to detect navigational hazards. As a result, lighthouses can continue to function optimally in supporting navigational safety without requiring direct human oversight at the site.

Figure 1. Transformed Lighthouse

In Indonesia, a similar innovation has been introduced by Hendaviny Kartomo, SE, M.Kom, a distinguished maritime transportation official currently serving as the head of *Kantor Distrik Navigasi Tipe A Kelas II Banjarmasin*. This initiative has been presented in various internal forums within the Directorate General of Sea Transportation and is

anticipated to offer a strategic solution to operational challenges in lighthouse management throughout the country.

The implementation of unmanning systems in Indonesian lighthouses requires comprehensive preparation, including the procurement of technological infrastructure and the training of operators to manage these systems. Through this modernization effort, it is expected that lighthouse management will become more efficient, maritime safety will be enhanced, and risks to operational personnel will be significantly reduced.



Source: Kemenhub RI 2024

Figure 2. Supporting Data for the Urgency of Lighthouse Transformation

The presented data underscores the urgent need for lighthouse modernization through the implementation of unmanning systems. Based on current statistics, Indonesia operates 285 lighthouses managed by 25 Navigation District Offices, with only around 491 technicians and operators assigned to oversee them. This translates to an average of fewer than two personnel per lighthouse, highlighting a significant limitation in human resources for both operational and maintenance tasks—especially in remote areas with challenging accessibility. Under such conditions, maintaining the consistent functionality of lighthouses becomes increasingly difficult, posing potential risks to maritime navigation and safety.

In addition, the shipping accident data reveals a notable fluctuation in incident rates. In 2020, there were 87 reported accidents, which increased to 100 in 2021. Although a decline was observed in 2022 and 2023, with 13 and 6 incidents respectively, the risk of maritime accidents remains a pressing concern. Contributing factors such as extreme weather conditions, river siltation due to sedimentation, and the lack of effective navigational aids amplify the dangers—especially in regions that encompass both marine and riverine navigation routes. These circumstances reinforce the necessity for continuous improvement in navigational safety measures.

Given the limited manpower and the operational challenges identified, the adoption of unmanning systems emerges as a highly promising solution to enhance lighthouse management efficiency. Technologies such as satellite-based monitoring, drones, and hazard-detecting radar can enable remote observation and control of lighthouses, thereby reducing the dependency on physical presence at each site. Such modernization efforts are expected to significantly bolster maritime safety by ensuring that lighthouses remain fully functional despite geographical or meteorological constraints.

Therefore, the optimization of lighthouse operations through unmanning systems presents a viable strategy to address these limitations by leveraging advanced technologies such as satellite surveillance applications, drone deployment, and radar-based navigation hazard detection.

This study will systematically examine the issue through the following stages: first, an analysis of the current state of lighthouse operations in Indonesia, including existing systems and management challenges; second, a comparative study of unmanning innovations in maritime navigation implemented by other countries to assess their applicability in the Indonesian context; third, an exploration of the technologies suitable for unmanning systems in lighthouse management, covering technical specifications, infrastructure requirements, and human resource preparedness. Furthermore, the research will evaluate the implications of implementing such systems in terms of regulatory frameworks, maritime policy, and their effectiveness in improving navigational safety.

Ultimately, this research aims to determine the extent to which unmanning systems can resolve existing challenges and to provide concrete recommendations for implementation steps that relevant authorities may undertake. Through this structured approach, the study aspires to make a meaningful contribution to the modernization of Indonesia's navigational infrastructure, particularly in enhancing the efficiency and safety of lighthouse operations.

THEORETICAL REVIEW

The theoretical foundation of this study draws upon several key frameworks that collectively support the rationale and implementation of unmanning systems in lighthouse modernization. First and foremost, Maritime Transportation Management provides a comprehensive understanding of how sea transportation systems are organized and operated, including the role of lighthouses as integral components of navigational infrastructure. This theory is essential in analyzing how the modernization of lighthouses through unmanning technologies can enhance the overall efficiency and effectiveness of maritime transport management. The correlation between improved operational systems and enhanced maritime safety is a critical focus of this research (Munandar, A., & Hidayat, B., 2020).

Next, the study leverages the theory of Maritime Navigation Technology, which explains the evolution and application of advanced navigational tools such as GPS, radar, and the Automatic Identification System (AIS). These technologies are directly applicable to unmanned lighthouse systems, enabling remote monitoring and control capabilities that reduce dependence on on-site personnel. The implementation of such technology not only optimizes operational efficiency but also extends the functional reach of lighthouses, especially in remote and logistically challenging regions (International Association of Marine Aids to Navigation and Lighthouse Authorities, 2021).

Closely related is the theory of Integrated Navigation Systems and AIS, which investigates how combining shipboard navigation systems with AIS can significantly improve the safety and efficiency of maritime navigation. Within this study, the integration between unmanned lighthouse systems and AIS is explored as a means of

delivering real-time information to vessels, thus enhancing situational awareness and minimizing accident risks, particularly in navigation-critical waterways. (Kurniawan, 2021)

Furthermore, the theory behind the implementation of e-Navigation is employed to examine how digital navigation systems can be utilized to modernize maritime infrastructure. E-Navigation encompasses the harmonized use of electronic systems to ensure safe and efficient navigation. In this context, the study evaluates how e-Navigation can support the unmanning of lighthouses through legal, policy-based, and institutional cooperation among maritime stakeholders. (Widodo, 2022)

Collectively, these theoretical frameworks form the foundation for a holistic analysis of lighthouse modernization through unmanning systems, addressing technological, managerial, operational, and regulatory dimensions of maritime safety and infrastructure development.

RESEARCH METHODS

This research adopts a qualitative approach by employing analytical methods, case studies, and literature reviews to develop a comprehensive understanding of lighthouse modernization through unmanning systems, with the primary aim of enhancing maritime safety.

The research process begins with the identification of core issues, particularly the operational limitations of lighthouses that remain heavily dependent on human resources. These challenges are compounded by Indonesia's vast and geographically complex archipelagic landscape, which poses significant logistical difficulties, and by the increasing risks associated with maritime navigation.

Following this, an extensive literature review is conducted, drawing on various sources such as academic journals, maritime regulations, and official reports related to navigational infrastructure and technological advancements in lighthouse management. This stage provides the conceptual and regulatory foundation necessary for further analysis.

The study then applies descriptive analysis to evaluate the current conditions of lighthouses in Indonesia. This includes an assessment of their total number, geographic distribution, and operational frameworks. Through this analysis, the study highlights existing gaps and areas for improvement in the management of lighthouse systems.

To enrich the analysis, the research incorporates case studies of successful unmanning implementations in other countries. These examples illustrate how remote technologies—such as satellite-based monitoring, radar systems, and unmanned aerial vehicles (drones)—have been effectively utilized to modernize lighthouse operations.

Finally, these international case studies are compared with Indonesia's current context to identify the challenges and opportunities associated with adopting similar technologies. The comparative evaluation seeks to determine the feasibility of implementation and to provide strategic insights that can guide national maritime authorities in advancing toward a more efficient and technology-driven lighthouse management system.

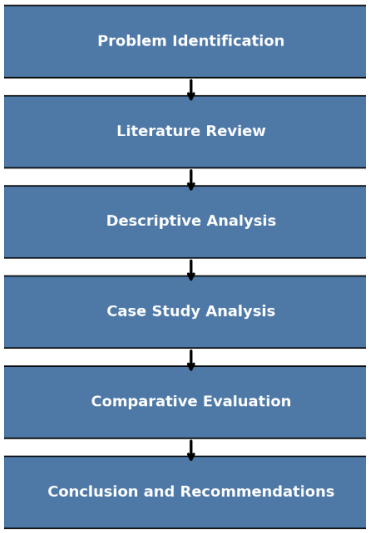


Figure 3. Research Methods

RESULTS AND DISCUSSION

The operational landscape of lighthouse management in Indonesia reveals a number of critical challenges that underscore the urgency of modernization through unmanning systems. ***Human resource dependency*** remains a fundamental issue, with only approximately 491 personnel—including technicians and operators—responsible

for managing 285 lighthouses across the archipelago. This limited manpower leads to excessive workloads and increased risk of fatigue, further compounded by low interest in lighthouse keeper positions, resulting in chronic understaffing for both operations and maintenance.

Operational inefficiency is another pressing concern. Many lighthouse facilities and equipment have exceeded a decade in service, yet maintenance remains suboptimal due to constrained budgets. Additionally, fuel budget limitations affect the frequency of maintenance vessel deployment, hindering routine upkeep of Aids to Navigation (AToN) infrastructure.

Indonesia's ***geographical complexity*** adds another layer of difficulty. With four of the world's seven major international shipping lanes crossing its waters, the country faces heightened maritime traffic density and associated security threats, such as piracy. The diverse topography and volatile marine weather conditions further complicate the task of ensuring consistent navigational safety.

Finally, ***navigational risks*** continue to escalate. Increased maritime traffic heightens the likelihood of collisions and other maritime incidents, while the vast expanse of Indonesian waters remains susceptible to unlawful activities such as piracy and hijacking. These factors collectively intensify the operational challenges of ensuring safe and secure maritime passage, and reinforce the strategic need for a technologically advanced, remotely operated lighthouse system.

Problem Identification: Human Dependency and Systemic Implications

One of the most fundamental issues in lighthouse management in Indonesia is the heavy reliance on human resources. According to data from the Directorate General of Sea Transportation, approximately 491 technical personnel are currently responsible for operating and maintaining hundreds of lighthouses dispersed across the Indonesian archipelago. This dependency creates a systemic issue, as the vast geographic distribution of the lighthouses is disproportionate to the limited number of staff available. Within the framework of organizational efficiency theory (Nasution, 2004), such a labor-intensive and manually operated public service system is considered non-adaptive to the evolving demands of modern maritime operations.

Consequently, when technical failures occur, response times and corrective actions are often delayed. This was exemplified by an incident in South Sulawesi waters in 2022, where a fishing vessel accident occurred due to a lighthouse being non-operational for two weeks, as technicians could not promptly reach the remote location. This case illustrates the high vulnerability of field operations that rely solely on human presence, especially when logistical infrastructure—such as marine transportation to the lighthouse site—is inadequate. In this context, the most rational solution lies in the transition toward a remote monitoring system based on unmanning technologies, which not only addresses human resource limitations but also enhances the reliability of navigational functions across Indonesia's waters.

Efficiency Aspect: Operational Ineffectiveness and Budget Constraints

Another compounding issue is the lack of efficiency in the operational and maintenance aspects of lighthouse infrastructure. Reports from the Ministry of Transportation through *Trans Laut* (2023) reveal that many lighthouse systems are using equipment that has been in service for over a decade, with little to no significant modernization. Budget limitations for fuel and maintenance are major obstacles to routine upkeep, especially given that maintenance vessels for AtoN (Aids to Navigation) must service multiple navigation points within one navigation district.

From the perspective of public infrastructure management theory, this reflects structural inefficiency in the maritime navigation system, which may result in systemic failure if left unaddressed. Ideally, in an archipelagic country such as Indonesia, the monitoring and operational systems for maritime infrastructure should depend on integrated and automated technologies rather than rotating on-site technician visits. Thus, the adoption of early-warning radar systems, satellite-based applications, and drone surveillance forms a vital part of the unmanning solution proposed in this research.

Geographical Challenges: Navigational Complexity in a Maritime Nation

Indonesia's geographical structure—as an archipelagic nation with over 17,000 islands and key international shipping lanes such as the Malacca Strait, Sunda Strait, and Lombok Strait—presents highly complex logistical and monitoring challenges. A study

by E-Journal Undip highlights that Indonesia oversees four of the world's seven major international sea routes, making its waters extremely busy and high-risk. Unfortunately, lighthouse monitoring and navigational infrastructure remain largely conventional and manually operated.

This situation becomes problematic as the geographic conditions do not allow for consistent manual monitoring. This is especially evident in regions with dual water characteristics, such as Kalimantan, where rapid sedimentation causes river shallowing and heightens navigational risks. Implementing unmanning systems using satellite monitoring and automated technologies can address these challenges more efficiently, enabling cross-location surveillance without requiring the physical presence of personnel at every point. This represents not only an adaptation to geographic complexity but also a response to the demand for modern, real-time, data-driven navigation systems.

Navigational Risk: Threats of Accidents and Maritime Security

Navigational risks in Indonesian waters are intensifying due to increased traffic and frequent incidents such as ship collisions, piracy, and the disappearance of AtoN. Reports from Deliveree Logistics indicate that routes such as the Sunda Strait record over 100 incidents annually. A primary contributing factor is the poor visibility of AtoN, often caused by damaged or inactive lighthouses. This is further supported by findings from STIA LAN, which state that many lighthouses are vulnerable to vandalism or neglect due to their remote, unsupervised locations.

In literature related to e-navigation and maritime risk management, automatic detection systems, route-monitoring radars, and digital maritime mapping are emphasized as key pillars in preventing marine accidents. The implementation of unmanning systems not only responds to efficiency and geographic challenges but also serves as a proactive safety measure that should be prioritized in national maritime transportation policy.

Reflection and Urgency: Unmanning as a Strategic and Innovative Solution

The above discussion highlights that the challenges surrounding lighthouses in Indonesia are not merely technical or administrative—they have reached a strategic and

systemic level. Human dependency, inefficiency, geographic barriers, and navigational risks form an interconnected set of issues that require an integrated technological breakthrough. The unmanning system, as proposed by Hendaviny Kartomo, SE., M.Kom., presents a visionary solution aligned with the global trend of maritime modernization. It directly addresses the core questions of this research: why the current system is ineffective, what alternatives exist, and how technology can provide concrete solutions.

Therefore, this study asserts that transforming lighthouse management into an unmanning system is not only a technological imperative but also a matter of national maritime safety. It advocates for structural reform in the management of AtoN, where human resources are no longer stationed in remote locations but are transitioned into operators of integrated monitoring systems housed in modern and responsive navigation district control centers.

Regulations Review

In advancing the argument for implementing an unmanned and remotely monitored lighthouse system in Indonesia, a multidimensional regulatory, empirical, and strategic framework underscores the urgency and legitimacy of such transformation. At the highest legal tier, *Undang-Undang No. 17 tentang Pelayaran* mandates the government's responsibility to ensure maritime safety and provide adequate aids to navigation (*SBNP*), thus laying the legal foundation for embracing technological modernization. This mandate is further elaborated through Transportation Ministerial Regulation *No. PM 25 of 2011*, which—while establishing governance standards—still operates within a conventional framework and omits explicit provisions for remote operation, predictive maintenance, or AI- and IoT-based automated monitoring. This regulatory asymmetry reveals a critical policy lag that this study seeks to address, offering evidence-based recommendations for reform aligned with global best practices.

Globally, the International Maritime Organization's (IMO) e-Navigation Strategy Implementation Plan (SIP) 2020 provides a pivotal reference point that situates the unmanning system within the broader evolutionary trajectory of maritime navigation.

The emphasis on digitalization, sensor integration, and spatial data convergence—through technologies such as AIS, maritime radar, and satellite mapping—reflects a paradigmatic shift in managing navigational risk and operational efficiency. Within this context, unmanning is not merely a technological innovation, but an embodiment of a systemic transformation in how maritime infrastructure is conceptualized and governed in the digital age.

Empirical studies further substantiate the technical and strategic relevance of this transition. The 2023 Performance Report of the Directorate General of Sea Transportation indicates that only 65% of national lighthouses are "optimally active," a statistic that underscores the fragility of human-dependent systems. Corresponding research, such as the Maritime and Logistics Journal (Vol. 5 No. 3, 2020), highlights the cascading economic impact of inactive lighthouses, including increased shipping deviations and logistical costs. In eastern Indonesia, as reported in the Journal of Sea Transportation (Vol. 9 No. 2, 2021), the absence of routine maintenance due to logistical constraints further illustrates the limitations of current operational models.

Technologically, evidence from multiple scientific publications confirms that Indonesia's readiness for unmanned infrastructure is already in its implementation phase. For instance, the ITS Journal of Engineering (Vol. 11 No. 1, 2022) validates microcontroller-based radar systems capable of detecting maritime hazards within a 3-nautical-mile radius. Similarly, the ITS Information Systems Journal (Vol. 10 No. 2, 2021) and the Journal of System Engineering and Technology (Vol. 4 No. 1, 2021) demonstrate the effectiveness of drone and AI-integrated IoT systems in enabling autonomous visual and spatial monitoring. These technologies have been successfully adopted in other sectors, confirming their feasibility and scalability.

What remains, therefore, is not a question of technological readiness, but of contextual adaptation—ensuring that these systems are tailored to the unique geographical, operational, and environmental challenges of Indonesia's archipelagic waters and diverse navigational districts. As emphasized in the World Bank's 2020 Maritime Infrastructure Report, investment in autonomous maritime technologies is

particularly crucial for archipelagic developing nations like Indonesia, where physical oversight of dispersed infrastructure is often infeasible.

This study thus positions itself not merely as a conceptual effort to modernize lighthouse operations, but as a transformational initiative—catalyzing a shift from static, labor-intensive systems to dynamic, intelligent infrastructure that is responsive, automated, and data-driven. Such an approach is not only aligned with Indonesia's vision of becoming a Global Maritime Fulcrum, but also constitutes a critical contribution to enhancing the resilience of the national maritime infrastructure amidst the growing complexity of 21st-century navigational risks.

Accidential Reports

Table 1. Case Report

Source: Kemenhub RI

No.	Accident Case	Date of Incident	Location	Primary Cause(s)	Relevance to Lighthouse Systems
1	Collision between KMP Bahuga Jaya and MV Norgas Cathinka	09/26/2012	Sunda Strait	Navigational and communication errors between both vessels	Not explicitly linked to lighthouse failure, but underscores the critical need for reliable navigational systems, including lighthouses.
2	Sinking of KM Sinar Bangun	06/18/2018	Lake Toba, North Sumatra	Overloading, unseaworthy vessel conditions, and lack of operational oversight	Not directly related to lighthouse systems, but highlights the need for strict regulatory enforcement and

					maritime monitoring.
3	Sinking of KM Cahaya Arafah	07/18/2022	South Halmahera Waters, North Maluku	Severe weather, limited weather information, and inadequate maritime telecommunications	Highlights the importance of accurate weather information and reliable communication systems, where lighthouses can serve as transmitters.
4	Fire onboard KM Karya Indah	05/29/2021	North Maluku Waters	Engine room fire due to non-compliant materials and lack of fire detection systems	Not directly linked to lighthouse infrastructure, but illustrates the need for early warning systems and remote monitoring, which lighthouses can support.
5	Sinking of KM Teratai Prima	01/11/2009	South Sulawesi Waters	Severe weather and potential overloading	Emphasizes the importance of early warning systems and navigational aids, including lighthouses, in conveying sea condition updates.

The case studies presented above clearly underscore that a significant number of maritime accidents in Indonesian waters are rooted in inadequate navigational

oversight, poor early warning systems, and limited integration of information technology in maritime traffic management. While lighthouses are not always directly implicated, these incidents reflect a broader systemic weakness in the performance of Aids to Navigation (*SBNP*), which could be substantially improved through modern technological approaches.

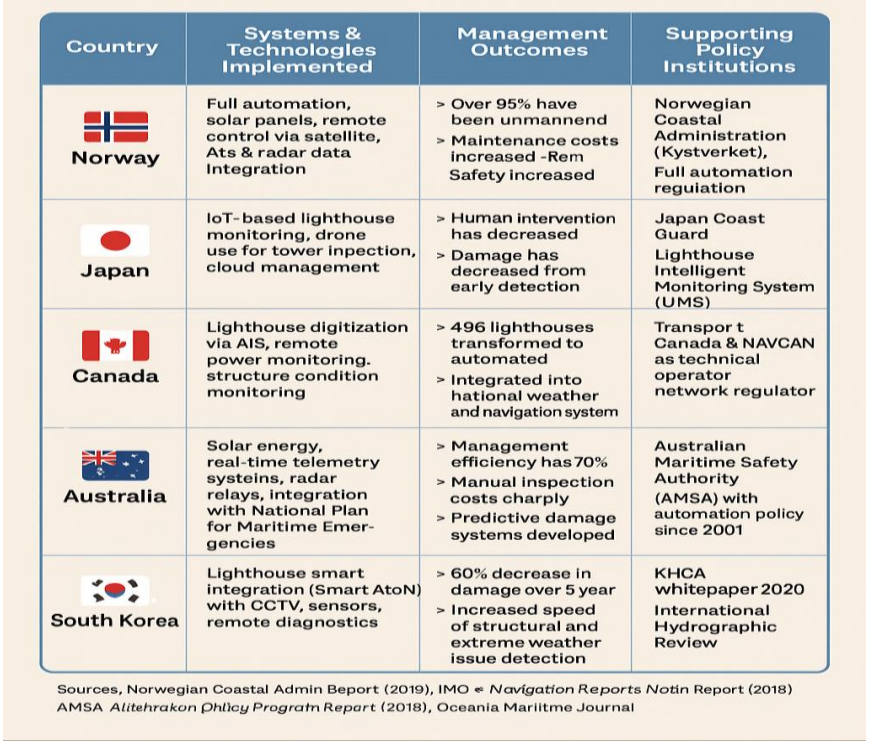
In this context, the implementation of unmanned lighthouse systems is not merely a step toward modernization—it is a strategic intervention to address structural limitations within the national maritime navigation framework. Incidents such as the KM Cahaya Arafah and KM Teratai Prima tragedies reveal how the absence of real-time weather, current, and traffic data contributed directly to disaster. Equipping lighthouses with automated weather sensors, radar, and satellite-based communication systems would elevate their function from passive markers to active data nodes—capable of anticipating and preventing accidents.

This aligns seamlessly with the International Maritime Organization's e-Navigation Strategy Implementation Plan, which promotes the integration of digital systems such as radar, AIS (Automatic Identification System), and spatial data to enhance maritime safety. Unfortunately, national regulations—most notably the Ministry of Transportation Regulation No. PM 25 of 2011—have yet to explicitly accommodate remote surveillance and automation within SBNP policy, thereby creating a normative bottleneck that impedes technological adoption.

Moreover, technical literature from engineering and maritime journals confirms the operational feasibility of unmanned lighthouse systems, already successfully implemented in countries with complex marine topographies. Technologies such as drone-based remote inspection, IoT sensors for structural and lighting monitoring, and cloud-based data processing are now standard in nations like Japan, Norway, and Canada. Given its vast archipelagic geography—home to over 17,000 islands and thousands of active shipping lanes—Indonesia arguably has an even greater imperative to deploy such systems.

By synthesizing factual accident data, regulatory gaps, and technological potential, this research asserts that unmanned lighthouse systems are not a discretionary

innovation but a strategic necessity for national maritime safety. Strengthening lighthouse infrastructure with smart technologies will lay the groundwork for a progressive, preventive, and resilient navigation system—essential for Indonesia's role as a Global Maritime Fulcrum.



Country	Systems & Technologies Implemented	Management Outcomes	Supporting Policy Institutions
Norway	Full automation, solar panels, remote control via satellite, Ats & radar data Integration	> Over 95% have been unmannend > Maintenance costs increased -Rem Safety increased	Norwegian Coastal Administration (Kystverket), Full automation reguiation
Japan	IoT-based lighthouse monitoring, drone use for tower inpection, cloud management	> Human intervention has decreased > Damage has decreased from early detection	Japan Coast Guard Lighthouse Intelligent Monitoring System (UMS)
Canada	Lighthouse digitization via AIS, remote power monitoring. structure condition monitoring	> 496 lighthouses transformed to automated > Integrated into hational weather and navigation system	Transpor t Canada & NAVCAN as technical operator network regulator
Australia	Solar energy, real-time telemetry systeins, radar relays, integration with National Plan for Maritime Emer-gencies	> Management efficiency has 70% > Manual inspection costs charply > Predictive damage systems developed	Australian Maritime Safety Authority (AMSA) with automation policy since 2001
South Korea	Lighthouse smart integration (Smart AtoN) with CCTV, sensors, remote diagnostics	> 60% decrease in damage over 5 year > Increased speed of structural and extreme weather issue detection	KHCA whitepaper 2020 International Hydrographic Review

Sources, Norwegian Coastal Admin Beport (2019), IMO ∞ *Navigation Reports Notin* Report (2018)
AMSA *Alitehrakon Phlicy Program Repart* (2018), Oceania Mariitme Journal

Figure 4. Internasional Comparative Study of Lighthouse Management Systems

Empirical and Theoretical Justifications for Unmanned Lighthouse Transformation in Indonesia

Empirical evidence from countries such as Norway, Japan, and South Korea demonstrates that the digital and unmanned transformation of lighthouses is not merely a technological ideal, but an operational and economic necessity. Norway, for instance, has successfully unmanned nearly all of its lighthouses since 2006, resulting in over 30% in annual operational cost savings and enhanced reliability in Arctic navigation. Theoretically, this aligns with Stopford's (2009) modernization theory, which underscores the centrality of real-time data integration in maritime transportation efficiency. Technologies such as radar, drones, satellite communications, and IoT have

redefined lighthouses from static structures to intelligent data-driven nodes, a core principle of the IALA-endorsed Smart AtoN concept. For Indonesia—a vast archipelagic state with over 20,000 islands and complex maritime routes—manual lighthouse management is no longer viable. Challenges in geographic accessibility, human fatigue, and limited monitoring capacity underscore the urgency for digital transformation. Case studies of past maritime accidents (e.g., KM Bahuga Jaya, KM Teratai Prima) further expose the fatal consequences of this gap. Moreover, regulatory inertia, as seen in the outdated PM 25/2011, hampers automation efforts, in stark contrast to countries with dedicated technical institutions such as NAVCAN (Canada) or KHOA (Korea). Innovations such as those proposed by Hendaviny Kartomo—leveraging satellite, radar, drone, and cloud-based monitoring—demonstrate that Indonesia has the domestic capability to implement a resilient unmanned system. Such systems can reduce human error, enable predictive diagnostics, and integrate spatial-temporal data into national logistics frameworks. In strategic areas like the Makassar Strait, unmanned systems can halve operational costs while enabling real-time, remote control of navigation aids. Ultimately, this research not only provides technical solutions but also offers a robust empirical and theoretical foundation for policy reform. It asserts that unmanning is not optional but a strategic imperative for maritime safety and efficiency. Therefore, Indonesia must urgently recalibrate its maritime navigation framework to be data-driven, digitally adaptive, and globally aligned.

CONCLUSION AND RECOMMENDATION

This research emerges as a critical response to the widening gap between rapid global advancements in maritime technology and the stagnation of Indonesia's management of Aids to Navigation (SBNP), particularly lighthouses—one of its most vital components. In an archipelagic nation where maritime routes serve as the backbone of logistics, connectivity, and national defense, outdated lighthouse management systems pose not merely a technical issue, but a matter of strategic national importance. The findings of this study reveal that continued reliance on human presence in lighthouse operations is both inefficient and increasingly untenable. Given Indonesia's geographical

complexity—ranging from deep seas and muddy rivers to extreme weather and logistical fragility—the conventional model is structurally incapable of meeting contemporary navigation demands.

Through descriptive analysis, literature review, and case studies, this research establishes that unmanned lighthouse systems are not futuristic ideals but logical and pragmatic necessities. Leveraging sensors, radar, telemetry, satellite monitoring, drones, and AI, lighthouses can be transformed into real-time, remotely operated infrastructure. The study supports the relevance of Technological Systems theory (Hughes, 1987) and Sociotechnical Transition theory (Geels, 2002), emphasizing that technological transformation must be accompanied by institutional reform and shifts in regulatory and human resource paradigms. Current policies, such as the Ministry of Transportation Regulation PM 25/2011, require revision to enable and encourage full automation. Notably, this innovation stems from within—spearheaded by Hendaviny Kartomo, SE, M.Kom.—proving that Indonesia's maritime human capital is capable of pioneering change. Thus, this research serves not only as an academic contribution but also as a potential policy blueprint for the modernization of national navigation systems. In essence, unmanned lighthouses are not just about illuminating sea routes—they represent Indonesia's commitment to a smarter, sovereign maritime future.

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