Strengthening National Capacity in Underwater Technology: Gap Analysis, Innovation Ecosystem, and Roadmap for 2026–2045

Muhsin Kahar

Master's Program in Ocean Engineering, Hasanuddin University
muhsinkahar@gmail.com

Abstract

Indonesia requires independent underwater-technology capabilities to support hydrographic survey, subsea infrastructure inspection, oceanographic research, environmental monitoring, search and rescue, and maritime defence. The initial manuscript identified technological gaps, limited laboratories, weak certification arrangements, human-resource constraints, and fragmented stakeholder collaboration. This revised study extends the analysis through a structured narrative review and policy analysis of national planning documents, international standards, and scientific literature on remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), navigation, communication, safety, and technology commercialisation. The assessment is organised into six capability dimensions: mission demand, critical technologies, testing facilities, standardisation and assurance, human competencies, and industrial-governance ecosystems. The results indicate that the principal constraint is not merely the ability to build prototypes, but the absence of an end-to-end evidence chain linking user requirements, design, relevant-environment testing, qualification, certification, procurement, and life-cycle support. A national strategy should therefore shift from fragmented prototype projects towards mission-driven programmes supported by open-system architectures, a national network of test facilities, early off-takers, and a Triple Helix governance structure with clear programme ownership. A four-phase roadmap for 2026–2045 is proposed: foundation, integration, industrial scaling, and technology leadership. Each phase is controlled through decision gates and measurable indicators, including technology readiness, domestic content, failure-free operating hours, certified products, qualified personnel, and industrial contracts. The framework provides a basis for research programming, facility investment, procurement reform, and national underwater-technology industrial development.

Keywords: underwater technology, ROV, AUV, national capability, Triple Helix, technology qualification, roadmap.

INTRODUCTION

Indonesia has a direct strategic interest in developing national capabilities in underwater technology, as maritime development encompasses marine resource management, infrastructure development, environmental protection, safety, defense, and marine spatial governance [1]. Indonesia's Ocean Policy also recognizes science and technology as one of the fundamental pillars for establishing sovereign, advanced, and sustainable ocean governance [2]. Furthermore, the Indonesian Ocean Policy Action Plan emphasizes the implementation of measurable cross-ministerial and interagency programs [3]. These policy directions are increasingly relevant to the National Long-Term Development Plan (RPJPN) 2025–2045 and the National Medium-Term Development Plan (RPJMN) 2025–2029, which identify economic transformation, research and innovation development, the blue economy, and industrial competitiveness as key priorities of national development [4], [5].

In this article, underwater technology is not limited to robotic vehicles. Its scope encompasses Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), underwater gliders, fixed underwater sensors, sonar systems, cameras, inertial and acoustic navigation systems, underwater communication technologies, pressure housings, power systems, command-and-control architectures, data processing, testing facilities, and safety and certification procedures. These components collectively form an integrated socio-technical system. For example, the operational success of an AUV depends not only on hull geometry and control algorithms but also on connector reliability, battery endurance, navigation data quality, recovery planning, operator competence, support vessel availability, testing-area authorization, and documented evidence of system fitness for operation.

The initial manuscript appropriately highlights a gap between the capability to develop prototypes and the ability to deliver products that can be routinely deployed by industry or government institutions. This issue is closely related to national research mandates [6], the institutional framework of the national science and technology system [7], and global marine science capacity, which remains highly dependent on infrastructure, equipment, specialized personnel, funding, and technology transfer mechanisms [8]. In many cases, projects do not progress beyond laboratory demonstrations because facilities for pressure testing, endurance testing, corrosion assessment, electromagnetic compatibility testing, sensor calibration, hardware-in-the-loop testing, and repeated sea trials are unavailable. Consequently, developed products may lack sufficient verification and validation evidence to support certification, procurement, and end-user acceptance.

Global technological developments indicate that underwater vehicles are increasingly evolving from standalone platforms into interconnected systems characterized by greater autonomy, multisensor capabilities, and extended

Lisensi Creative Commons Atribusi 4.0 Internasional.

operational endurance. The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) promotes improvements in ocean knowledge, data availability, research infrastructure, and technological capacity to support evidence-based decision-making [9]. At the same time, AUV-related literature identifies navigation, underwater communication, energy management, environmental perception, docking, safety, and mission planning as critical technological challenges [17]–[26]. Indonesia therefore needs to identify realistic technological entry points to avoid merely following global trends and instead develop competencies aligned with national operational requirements.

This study aims to revise and expand the initial manuscript through four principal contributions. First, it develops a capability taxonomy that distinguishes mission requirements, systems, subsystems, testing facilities, professional competencies, and governance mechanisms. Second, it establishes a qualitative gap analysis without claiming national technology readiness levels that are unsupported by a publicly available capability inventory. Third, it formulates an operational Triple Helix model connecting universities and research institutions, industrial partners and off-takers, and government agencies and standardization bodies within a mission-oriented program. Fourth, it proposes a national underwater technology roadmap for 2026–2045 incorporating decision gates, key performance indicators, implementation risks, and program priorities.

CONCEPTUAL FOUNDATIONS AND SCOPE

Taxonomy of Underwater Technologies

Underwater technology can be understood as a collection of technologies that enable sensing, intervention, communication, transportation, and decision-making beneath the water surface. ROVs are generally controlled through tethered connections and are suitable for visual inspections, manipulation tasks, and intervention operations requiring real-time data communication. AUVs operate without tethers and perform missions based on predefined commands, onboard sensors, and embedded algorithms. Underwater gliders use buoyancy variation to achieve energy-efficient movement and are suitable for long-term oceanographic observations. Fixed sensor systems and underwater acoustic networks complement mobile vehicles by providing continuous environmental observations.

From a systems engineering perspective, the platform is the most visible layer of underwater technology; however, its strategic value is largely determined by its subsystems. These include pressure-resistant structures, sealing systems, propulsion, energy storage, power management, navigation, control, payloads, communication, mission software, data processing, launch-and-recovery systems, and maintenance capabilities. The literature indicates that AUV development is strongly influenced by advances in propulsion, sensors, computing, control, navigation, and energy technologies [19]. Meanwhile, contemporary underwater navigation surveys classify navigation approaches into dead reckoning, signal-based navigation, and geophysical navigation [20]. Accordingly, national technology policies should not merely establish targets for developing AUV platforms but should also identify which subsystems can be designed, integrated, manufactured, and supported domestically.

Underwater communication faces fundamental technological limitations. Acoustic networks are constrained by low bandwidth, propagation delays, multipath interference, fading, and energy consumption [23]. Optical communication offers higher data transmission rates and lower latency; however, its operational range is strongly influenced by absorption, scattering, and water clarity [24]. Consequently, underwater communication architectures should employ hybrid approaches tailored to specific mission requirements. Optical links may be suitable for short-range inspections, acoustic modems remain important for longer-range communication, and large-volume data transfer can be performed after docking or vehicle recovery.

Innovation Systems, the Triple Helix Model, and Off-Takers

The Triple Helix model conceptualizes innovation as the result of interactions among universities, industry, and government rather than a linear progression from scientific research to commercial markets [10]. In underwater technology development, these interactions must be translated into clearly defined institutional responsibilities. Universities and research institutions contribute scientific concepts, mathematical models, algorithms, prototypes, and skilled personnel. Industry is responsible for design for manufacturability, system integration, production, quality assurance, maintenance, and operational support. Government institutions establish strategic missions, provide shared facilities, develop standardization frameworks, regulate procurement, and reduce initial market risks.

The involvement of off-takers represents a critical distinction between symbolic institutional collaboration and partnerships capable of producing operationally deployable products. An off-taker is an early adopter or prospective user who provides actual operational requirements, environmental data, acceptance criteria, testing locations, operational personnel, and potential contractual opportunities. Without off-takers, technical specifications may evolve according to researchers' interests rather than genuine mission requirements. International practices in public research commercialization also emphasize the importance of licensing, spin-offs, collaborative research, technology demonstrators, and procurement mechanisms in connecting publicly generated knowledge with economic applications [11].

Lisensi Creative Commons Atribusi 4.0 Internasional.

Technology Readiness and Technology Qualification

Technology Readiness Levels (TRLs) provide a common framework for evaluating technological maturity, from basic scientific principles to systems demonstrated in operational environments. ISO 16290 establishes TRL assessment criteria to reduce dependence on subjective judgments [12]. However, TRL is not the only relevant indicator. A system may exhibit a high TRL at the subsystem level while failing during integration because of interface incompatibilities, software limitations, operator requirements, environmental constraints, or supply chain issues. Therefore, a national technology roadmap should integrate TRL with manufacturing readiness, integration readiness, reliability growth, certification readiness, and operational readiness.

Technology qualification is the process of generating documented evidence that a system can satisfy specified requirements under relevant environmental conditions while maintaining an acceptable level of risk. For AUVs, ISO 20682:2026 addresses risk and reliability considerations associated with design and operation [13]. ISO 25451:2026 also provides requirements and guidelines for seabed mapping using unmanned marine vehicles, covering navigation, vehicle configurations, survey parameters, echo sounding, and data processing [14]. These developments in international standards indicate that technological independence involves not only the ability to manufacture equipment but also the capacity to demonstrate performance, safety, data quality, and operational consistency.

Standardization, Classification, and Assurance

Technology assurance encompasses design reviews, risk assessments, verification, validation, testing, configuration control, software assurance, cybersecurity, and competency audits. International classification societies have established classification and certification services for ROVs, AUVs, unmanned underwater systems, ocean monitoring systems, and associated subsystems and equipment [15]. In hydrography, the International Hydrographic Organization (IHO) S-44 standard emphasizes accuracy, survey coverage, and seabed feature detection capabilities according to the relevant survey order [16]. This demonstrates that underwater technology products should be assessed against their intended mission requirements rather than solely according to their ability to navigate or operate underwater.



Figure 1. Research framework and analytical workflow.

For Indonesia, strengthening the roles of Biro Klasifikasi Indonesia (BKI), calibration laboratories, standardization bodies, educational institutions, and end-users requires coordinated institutional development. National standards may adopt or adapt international requirements while considering tropical marine environments, high turbidity, biofouling, local current conditions, archipelagic logistics challenges, and variations in operational depth. The objective is not to introduce unnecessarily restrictive requirements that inhibit innovation but to establish clear, transparent, and risk-proportionate pathways for technological qualification and acceptance.

METHODS

Review Design

This study employed a structured narrative review and policy analysis. This approach was selected because the objective was not to calculate pooled effect sizes but to synthesize technical, institutional, and policy evidence obtained from different types of sources. The original manuscript served as the foundation for retaining four principal areas of investigation: technological gaps; testing facilities, certification, and human resources; Triple Helix collaboration; and the national technology development roadmap. These areas were subsequently expanded into an end-to-end capability development framework.

Lisensi Creative Commons Atribusi 4.0 Internasional.

The sources included national legislation and development planning documents, reports issued by international organizations, ISO and IHO standards, classification practices, and scientific articles addressing AUVs and ROVs, navigation, sensor fusion, underwater communication, docking technologies, and risk analysis. The principal publication period covered 2000–2026, while selected earlier foundational sources were retained when they remained conceptually relevant. Priority was given to official documents, technical standards, peer-reviewed journal articles, and established engineering reference books.

Analytical Framework

Each source was qualitatively coded into six analytical dimensions: (1) mission requirements and end-user demand; (2) systems, subsystems, and critical components; (3) testing facilities and sea trials; (4) standardization, safety, and assurance; (5) competencies and human resource development pathways; and (6) industry, financing, procurement, and governance. The resulting findings were synthesized into a technological gap matrix, a portfolio of priority programs, an institutional responsibility framework, and a national technology development roadmap. The classifications of low, medium, and high priority were applied exclusively as qualitative assessments based on operational consequences and implementation urgency. These classifications were not intended to represent national statistical scores or quantitatively measured technological readiness.

Research Limitations

This study did not employ a comprehensive inventory of all Indonesian underwater technology laboratories, industrial facilities, products, patents, personnel, and development projects because a consistent and publicly accessible national database was not available. Consequently, the study does not quantitatively assign a single Technology Readiness Level (TRL) to Indonesia's overall underwater technological capabilities. The proposed roadmap therefore represents a strategic framework requiring further calibration through a national capability audit, stakeholder surveys, and validation workshops. In addition, sensitive defense-related issues were addressed at the general policy level without incorporating classified operational information or technical specifications.

RESULTS AND DISCUSSION

Mapping National Mission Requirements

National technological capability development should be driven primarily by *mission pull* rather than *technology push*. A mission-pull approach begins with end-users defining operational problems, environmental conditions, expected outputs, accuracy requirements, endurance, acceptable risks, and cost constraints. Research institutions and industrial partners subsequently select technological architectures capable of meeting these requirements. Table 1 presents examples of national mission categories and the critical technologies associated with them. The list is not intended to serve as a definitive national technology catalogue but rather as a preliminary foundation for establishing a mission-oriented development portfolio.

Table 1. Mission categories, operational requirements, and critical technologies**.**

Mission category	Principal operational requirements	Critical technologies	Potential early users
Hydrographic surveying and seabed mapping	High survey coverage, positioning accuracy, data quality, and shallow- to deep-water operation	Multibeam/side-scan sonar, INS–DVL–USBL, mission planning, quality control	Pushidrosal, BRIN, KKP, port operators, survey consultants
Subsea infrastructure inspection	Visualization, anomaly detection, thickness measurement, and light manipulation	ROVs, imaging sonar, camera and lighting systems, NDT payloads, tether management	Oil and gas operators, telecommunications cable operators, offshore energy companies
Oceanography and environmental monitoring	Extended endurance, sampling, time-series data, and low operating costs	Underwater gliders, CTD/DO sensors, acoustic networks, data telemetry	BRIN, universities, KKP, BMKG
Search and rescue	Rapid mobilization, area searching, target classification, and recovery	Observation-class ROVs, side-scan sonar, positioning systems, command centers	Basarnas, Indonesian Navy, Bakamla, marine police
Defense and maritime security	Surveillance, mine countermeasures, secure communication, and low observability	AUVs, sonar, autonomous systems, secure communication, cooperative missions	Indonesian Navy and maritime security agencies

Lisensi Creative Commons Atribusi 4.0 Internasional.

Mission category	Principal operational requirements	Critical technologies	Potential early users
Underwater construction and maintenance	Intervention, specialized tooling, force feedback, and high reliability	Work-class ROVs, manipulators, hydraulic power systems, subsea tooling	Oil and gas operators, subsea contractors, shipyards, system integrators

Capability Architecture and Failure Points in the Value Chain

The synthesis indicates that national underwater technological capability should be understood as five interdependent layers: mission and market requirements, systems and platforms, critical technologies, testing and assurance infrastructure, and the supporting innovation ecosystem. Figure 2 illustrates the relationships among these layers. Weaknesses in foundational capabilities can constrain the development and deployment of higher-level technological systems. For example, an AUV design may be completed successfully, but without access to pressure chambers and validated sealing procedures, sufficient confidence cannot be established for deeper-water operations. Similarly, a system may successfully complete technical testing but remain commercially unused if procurement mechanisms, spare parts support, and operational safety assurance are unavailable.

Import dependence should therefore be evaluated at the functional and interface levels rather than merely by counting imported components. The initial use of imported thrusters, for example, may be acceptable if domestic developers control the mechanical, electrical, and communication interfaces, allowing alternative suppliers to be integrated when necessary. Conversely, dependence on proprietary mission software, closed communication protocols, or inaccessible data formats can create long-term technological lock-in. Open system architectures and control over Interface Control Documents (ICDs) should therefore be established as fundamental design principles from the initial capability development phase.



Figure 2. National underwater technology capability architecture.

Priority Gap Analysis

The capability gap matrix presented in Table 2 was developed by comparing the requirements for repeatedly deployable underwater systems with the recurring challenges identified in the original manuscript and relevant literature. Very high priority was assigned to factors capable of causing an entire technology development program to fail even when a functional prototype had already been produced.

Table 2. Priority capability gap matrix.

Dimension	Common capability gap	Potential consequences	Development priority
Requirements and CONOPS	Specifications driven by technological features rather than user needs	Prototypes fail to satisfy operational requirements and acceptance criteria	Very high
Pressure integrity and sealing	Limited depth testing and inconsistent evidence for materials and sealing	Leakage, vehicle loss, and safety risks	Very high
Navigation and positioning	Dependence on imported sensors and ad hoc integration	Positioning drift and survey data that fail to meet required standards	Very high
Energy and endurance	Inadequate integration of battery packs, BMS, thermal management, and charging systems	Short mission duration, power failures, and thermal risks	High

Lisensi Creative Commons Atribusi 4.0 Internasional.

Dimension	Common capability gap	Potential consequences	Development priority
Communication and data	Limited bandwidth, proprietary protocols, and fragmented data pipelines	Unreliable control and decision-making	High
Testing facilities	Disconnected pressure chambers, calibration facilities, HIL systems, test basins, and sea-trial infrastructure	Expensive, slow, and poorly reproducible testing	Very high
Standardization and certification	Unclear product acceptance pathways and insufficient staged evidence requirements	Reluctance among users to purchase and operate domestic systems	Very high
Human resources and operations	Fragmented competencies among designers, pilots, technicians, mission planners, and safety officers	Inconsistent operations and loss of institutional knowledge	High
Supply chain and MRO	Inadequate control of critical components, configurations, spare parts, and documentation	High downtime and uncertain lifecycle costs	High
Procurement and off-takers	Procurement contracts focused on purchasing units without demonstration or learning periods	Domestic products cannot build operational track records before competing commercially	Very high

Laboratory Infrastructure and a National Sea-Trial Network

The development of underwater technology does not require every testing facility to be located within a single institution. A more efficient approach would be to establish a **national distributed test network**, in which laboratories with different technical specializations operate under integrated procedures, data formats, and facility booking mechanisms. The network should support a progressive testing sequence, beginning with material and component testing, followed by subsystem testing, integrated system evaluation, and ultimately sea trials. The proposed core facilities are presented in Table 3. Hyperbaric pressure chambers are particularly important for evaluating pressure housings, penetrators, connectors, battery enclosures, and underwater sensors. Nevertheless, static pressure testing alone is insufficient to establish operational reliability.

Systems should also be evaluated for cyclic pressure exposure, soaking duration, temperature variation, leakage, corrosion, vibration, mechanical shock, electromagnetic compatibility, and long-duration operation. Software and autonomous systems require complementary verification infrastructure, including numerical simulators, hardware-in-the-loop (HIL) facilities, digital twins, fault-injection environments, and recorded-data replay capabilities. Sea trials should be conducted within progressively demanding testing environments. Sheltered waters can be used for commissioning, coastal testing sites for intermediate operational missions, and deep-water locations for more advanced qualification activities. Testing facilities should implement governance procedures that ensure traceability of equipment identity, configuration, instrument calibration, testing procedures, environmental conditions, raw data, anomaly logs, acceptance decisions, and lessons learned. Without these records, testing campaigns may produce only visual demonstrations rather than reproducible evidence suitable for certification, procurement, or operational acceptance.

Table 3. Core testing facilities and qualification evidence.

Facility	Principal function	Evidence generated	Proposed management model
Pressure chambers and leakage testing	Static/cyclic pressure testing, sealing, penetrators, and enclosures	Pressure curves, leakage rates, inspection records, failure modes	Accredited national or regional centers
Towing tanks and maneuvering basins	Drag, stability, control response, launch and recovery	Hydrodynamic coefficients, trajectories, repeatability	University–BRIN–industry consortia
Sensor calibration laboratories	Calibration of CTD, pressure, compass, acoustic sensors, and cameras	Calibration certificates, uncertainty budgets, measurement traceability	Accredited laboratories
Electrical, battery, and EMC laboratories	BMS, endurance, thermal response, vibration, and EMC testing	Power profiles, thermal margins, safety evidence	Shared industrial laboratories
Software/HIL testbeds	Mission software, navigation, control, and fault injection	Requirements coverage, test reports, failure responses	Open testing platforms with data replay
Sea-trial corridors	Relevant-environment testing and end-to-end operations	Operating hours, recovery success, data quality, anomaly logs	Integrated permitting and safety governance

Lisensi Creative Commons Atribusi 4.0 Internasional.

Facility	Principal function	Evidence generated	Proposed management model
Data repositories	Storage of configurations, raw data, test evidence, and lessons learned	Digital evidence packages and performance baselines	National underwater technology data trust

Navigation, Perception, Communication, and Autonomy

Navigation is one of the most important factors determining AUV mission success because Global Navigation Satellite System (GNSS) signals are generally unavailable while a vehicle is submerged. Underwater navigation systems therefore commonly integrate inertial navigation systems, Doppler velocity logs, depth sensors, compasses, acoustic positioning systems, and environment-based sensing technologies. Reviews of unmanned underwater vehicle positioning emphasize the importance of integrating acoustic systems, inertial navigation, DVL measurements, geophysical techniques, and sensor fusion [21]. Developments in sensor fusion and underwater Simultaneous Localization and Mapping (SLAM) have sought to reduce positioning drift and improve environmental perception [22]. However, performance remains strongly influenced by sensor calibration quality, time synchronization, measurement noise, seabed characteristics, and system observability.

National technology development should not immediately prioritize the most complex forms of autonomy. Initial priorities should focus on **reliable autonomy**, including predictable mission execution, geofencing, abort logic, fault detection, health monitoring, safe-state transitions, and vehicle recovery. After sufficient operational evidence has been accumulated, these capabilities can be progressively extended toward adaptive path planning, cooperative AUV operations, and swarm autonomy. The literature on path planning and risk analysis indicates that increasing autonomy must be accompanied by systematic risk modeling, algorithm validation, and safety monitoring [25], [27], [28]. In underwater communication, the development of domestic modems should be integrated with communication protocol development and network management capabilities. The limitations of acoustic channels [23] and optical communication technologies [24] demonstrate that no single communication method can satisfy every mission requirement. Technology development programs should therefore incorporate modular payload bays, software-defined interfaces, and protocol gateways that enable platforms to combine acoustic links, optical links, radio-frequency communication at the surface, satellite communication, and tethered connections according to operational requirements.

Standardization, Certification, and Staged Assurance Models

Domestic technology developers frequently encounter a qualification dilemma: prospective users require certification before purchasing equipment, while certification itself requires financial resources and operational evidence that emerging products may not yet possess. A practical response is to establish a staged, risk-based assurance system. In the first stage, assessors evaluate mission requirements, design bases, materials, interfaces, and risk registers. The second stage examines the results of component and subsystem testing. The third stage evaluates integrated laboratory testing and sea trials. The final stage provides approval for a defined operational envelope rather than unrestricted authorization for all operating conditions. ISO 20682:2026 provides a framework for AUV risk and reliability considerations [13], while DNV classification practices demonstrate that ROVs, AUVs, unmanned underwater systems, monitoring systems, and associated subsystems may undergo classification or certification through design assessment, testing, risk analysis, and technical support [15].

For hydrographic missions, output data quality should also be aligned with relevant IHO survey standards and data requirements [16]. Through this approach, certification becomes a mechanism for engineering learning and progressive design improvement rather than a purely administrative requirement. Biro Klasifikasi Indonesia (BKI) could serve as a national assurance integrator through collaboration with the National Standardization Agency (BSN), National Accreditation Committee (KAN), laboratories, operators, universities, and relevant international organizations. Initial initiatives could include national guidelines for observation-class ROVs, sea-trial procedures, operator competencies, and acceptance testing. As national capabilities mature, these guidelines could progressively evolve into more comprehensive rules for AUVs, work-class ROVs, and underwater monitoring systems.

Lisensi Creative Commons Atribusi 4.0 Internasional.

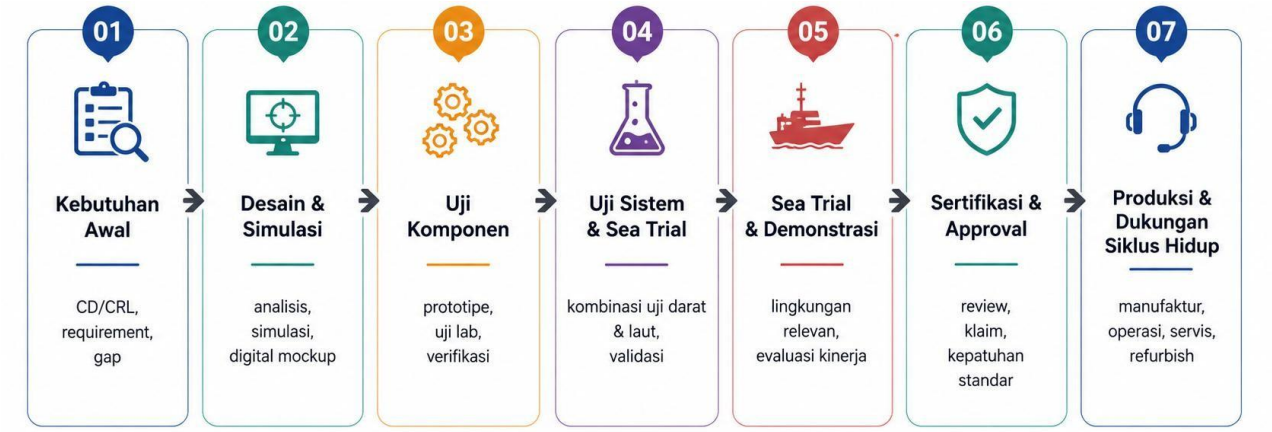


Figure 3. Evidence-based stages of technology qualification and commercialization.

Human Resource Competencies and Professional Development Pathways

Underwater technology development requires multidisciplinary teams with complementary engineering, operational, and assurance competencies. Human resource gaps cannot be addressed solely by establishing a new academic degree program. A more realistic strategy is to develop a national competency framework linking formal education, microcredentials, professional certification, apprenticeships, and practical operational experience. Competencies should be differentiated according to professional responsibilities, including system engineers, system integrators, operators, technicians, data specialists, and safety and assurance personnel.

Educational programs should integrate theoretical understanding with the development of engineering evidence. Students should not be limited to producing prototypes for demonstration purposes. They should also acquire experience in developing requirements, interface control documentation, risk registers, test plans, configuration baselines, calibration records, and post-mission reports. Industrial organizations can contribute operational problem statements, equipment loans, technical mentors, and internship opportunities. Government institutions can support teaching factories, fellowship programs, and professional certification pathways.

Table 4. Human resource competency framework for underwater technology.

Competency group	Core competencies	Development pathway	Evidence of competence
System engineer	Requirements, architecture, interfaces, verification and validation, trade-off analysis	Postgraduate/professional education, project-based learning, industry mentoring	System design reviews and evidence packages
Mechanical/pressure engineer	Pressure vessels, sealing, corrosion, materials, manufacturing	Design courses, manufacturing workshops, pressure testing	Qualified designs and test reports
Electrical/power engineer	Batteries, BMS, power distribution, EMC, sensor interfaces	Laboratory training and vendor certification	Endurance, thermal, and EMC reports
Navigation/control/software engineer	INS/DVL/USBL, estimation, control, autonomy, simulation	Research projects, HIL testing, code reviews, field testing	Requirements coverage and mission logs
ROV/AUV operator	Mission planning, piloting, recovery, emergency response	Simulators, apprenticeships, operational sea time	Operational logbooks and competency assessments
Technician/MRO	Assembly, sealing, connectors, troubleshooting, calibration	Vocational programs and OEM training	Maintenance task sign-off
Data and hydrography specialist	Data quality, sonar processing, uncertainty, metadata	IHO-aligned training and software practice	Survey reports and quality-control evidence
Safety and assurance specialist	Risk assessment, FMEA, verification, audits, incident learning	Professional certification and assessor training	Approved risk assessments and audit reports

Lisensi Creative Commons Atribusi 4.0 Internasional.

Operational Triple Helix Model

Institutional collaboration may become ineffective when each participant remains confined to its traditional role. Universities prioritize scientific publications, industry waits for mature technologies, and government institutions finance separate annual projects. The proposed framework transforms these relationships into a program partnership model**.** Each program should have a designated mission owner, technical authority, system integrator, lead laboratory, assessor, and off-taker. This organizational structure establishes clear accountability while maintaining contributions from multiple institutions. As illustrated in Figure 4, the central mechanism of collaboration should not be limited to coordination meetings. Instead, it should consist of joint programs that produce operational requirements, demonstrators, testing campaigns, certification evidence, procurement pathways, and lifecycle support capabilities. Table 5 outlines the principal responsibilities of the participating institutions.

Table 5. Allocation of responsibilities within the program partnership model.

Function	Universities/BRIN	Industry/off-takers	Government/standardization bodies
Requirement definition	Technical analysis and feasibility assessment	Operational use cases, data, and acceptance criteria	Priority mission definition and program ownership
Research and design	Models, algorithms, prototypes, and experiments	Design for manufacturability and system integration	Multiyear funding and access to facilities
Testing	Test methods, instrumentation, and analysis	Unit testing, production testing, and sea-trial operations	Testing corridors, permits, accreditation, and safety oversight
Assurance	Evidence generation and independent review	Configuration control and corrective actions	Standards, assessment, certification, and approval
Commercialization	Intellectual property management, spin-offs, and training	Manufacturing, MRO, warranties, and supply chains	Procurement, phased local-content policies, and early-market incentives
Organizational learning	Curricula, theses, and scientific publications	Apprenticeships and lessons learned	National repositories and program evaluation

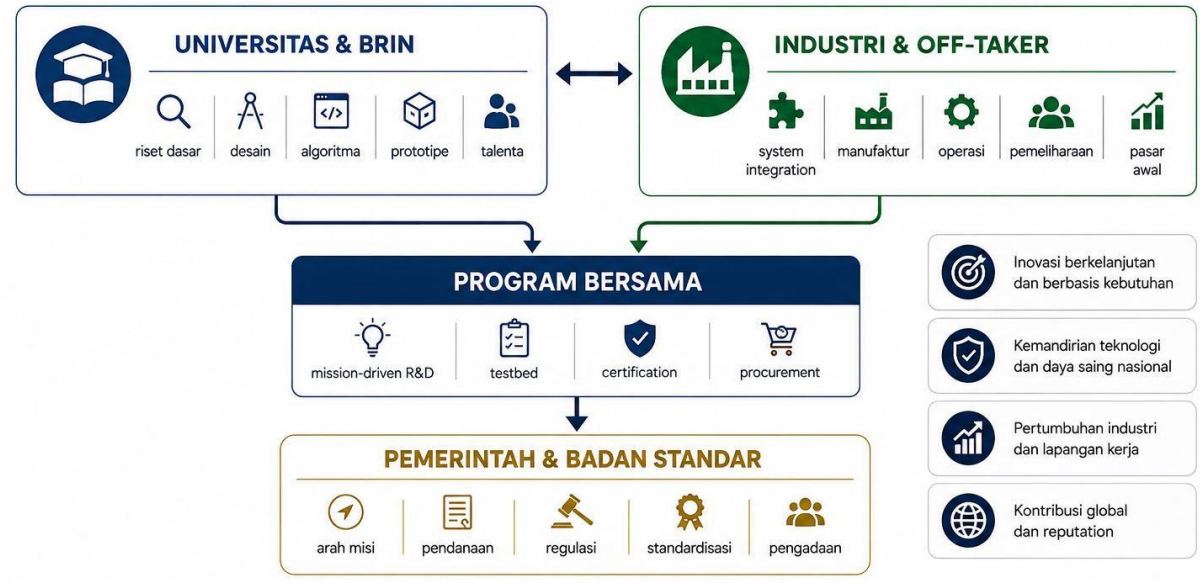


Figure 4. Operational Triple Helix model for underwater technology development.

Priority Program Portfolio for 2026–2030

The foundation phase should concentrate resources on programs capable of generating substantial capability-building effects. An excessive number of small, disconnected projects may reproduce existing institutional fragmentation. Therefore, the eight priority programs presented in Table 6 were selected because they contribute to a common capability stack that can support multiple underwater missions.

Lisensi Creative Commons Atribusi 4.0 Internasional.

Table 6. Priority program portfolio for the foundation phase.

Priority program	Target output by 2030	Proposed lead institutions	Principal performance indicators
National observation-class ROV	Modular 300 m-rated platform, standardized payloads, open data interfaces	University–BRIN–system integrator consortium	At least 1,000 cumulative operating hours; measured availability
AUV mapping demonstrator	Coastal mapping AUV integrating INS/DVL/acoustic aiding	BRIN, universities, and survey industry	Survey data meeting selected mission acceptance criteria
Pressure and subsea component center	Pressure chambers, sealing qualification, connector and housing database	BRIN, BKI, universities, and industry	Number of qualified components and availability of failure records
Underwater navigation and autonomy stack	Middleware, navigation estimator, mission manager, abort logic, simulator	Universities, BRIN, and software integrators	Test coverage, HIL operating hours, sea-trial success rate
Acoustic communication program	Modems, protocols, gateways, and field-channel database	Electrical engineering universities and telecommunications industry	Range–data-rate–energy performance mapping in Indonesian waters
National sea-trial corridor	Sheltered-water, coastal, and deep-water testing zones	Local governments, maritime institutions, and BRIN	Number of testing campaigns, safety performance, data reuse
Competency and certification scheme	Role-based curricula and operator, technician, and assessor pathways	Universities, BNSP, BKI, and industry	Number of certified personnel and accumulated operational sea time
First-buyer procurement mechanism	Demonstration contracts, pilot operations, service-based procurement	Government ministries, agencies, and state-owned end-users	Number of contracts, local value creation, repeat orders

National Underwater Technology Roadmap for 2026–2045

The proposed roadmap is divided into four phases to ensure that technological ambitions advance in accordance with demonstrated capabilities. Each phase incorporates decision gates. Programs should progress to subsequent phases only when technical, operational, industrial, and governance evidence satisfies the established criteria. This approach reduces the risk of establishing symbolic technology development targets without sufficient operational capability to support their achievement.

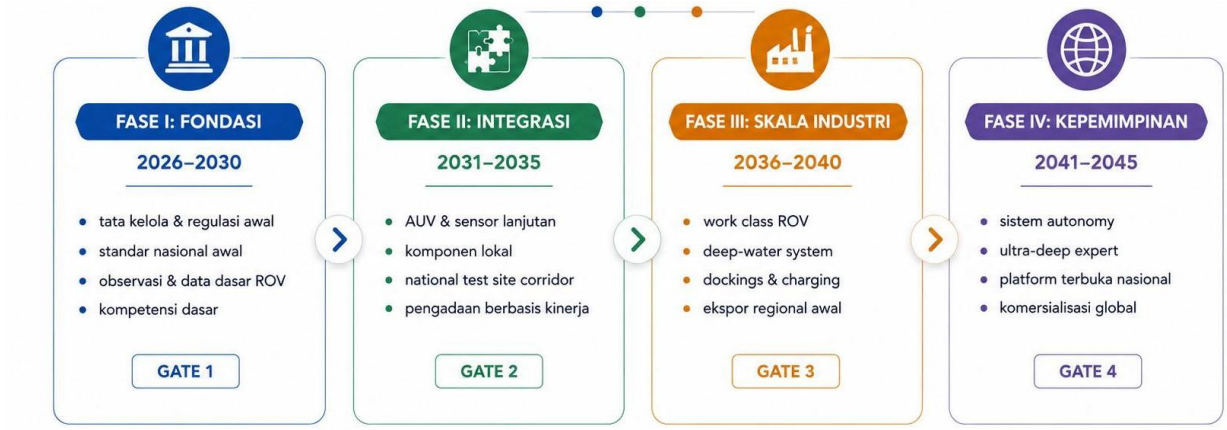


Figure 5. National underwater technology capacity development roadmap for 2026–2045.

Phase I (2026–2030) focuses on establishing foundational capabilities, including a national capability audit, core testing facilities, observation-class ROV platforms, coastal AUV mapping demonstrators, initial testing standards, and competency development schemes.

Phase II (2031–2035) emphasizes system integration through semi-autonomous AUV development, domestic critical components, testing corridors, open architectures, and performance-based procurement mechanisms.

Phase III (2036–2040) aims to expand industrial scale through work-class ROV development, deep-water systems, docking and charging technologies, and initial regional exports.

Lisensi Creative Commons Atribusi 4.0 Internasional.

Phase IV (2041–2045) targets technological leadership in swarm autonomy, ultra-deep-water systems, data interoperability, and global commercialization.

The roadmap does not consider operating depth or domestic component content to be sufficient indicators of technological independence. A system capable of operating at considerable depth but lacking reliability, high-quality data, or domestic maintenance support cannot be regarded as fully demonstrating national technological capability.

Consequently, cross-phase performance indicators should address reliability, availability, maintainability, data quality, certification, human resource competence, industrial contracts, and total cost of ownership.

Table 7. Milestones and decision gates for the national roadmap.

Phase	Technical milestones	Ecosystem milestones	Decision gates
I. Foundation, 2026–2030	Modular 300 m ROV; coastal AUV demonstrator; pressure, HIL, and sea-trial facilities	Testing guidelines; competency schemes; first-buyer pilots; national inventory	Validated requirements, available testing evidence, at least two active off-takers
II. Integration, 2031–2035	Semi-autonomous AUVs; domestic critical components; acoustic networks; common software stack	Advanced national standards, supply chains, service/performance-based procurement	Demonstrated reliability growth and repeat orders
III. Industrial scaling, 2036–2040	Work-class ROVs; deep-water payloads; docking/charging; multi-vehicle operations	Production quality systems, MRO networks, initial regional exports	Certified products, repeated commercial operations, viable unit economics
IV. Technological leadership, 2041–2045	Ultra-deep-water systems; cooperative/swarm autonomy; integrated seabed observatories	National open platforms, international certification, global partnerships	Regional/global market position and continuous innovation pipeline

Financing, Procurement, and Business Models

Annual research funding arrangements are often poorly suited to technologies requiring repeated design–test–improve cycles. Priority programs should therefore adopt multiyear financing mechanisms linked to clearly defined milestones. Funding disbursement should not depend solely on written reports or prototype delivery. Instead, it should be linked to documented evidence, including design reviews, test readiness reviews, experimental results, closure of corrective actions, sea-trial operating hours, demonstrated reliability growth, and end-user acceptance. Such mechanisms can preserve accountability because each development stage has objectively verifiable deliverables. Procurement arrangements should also distinguish between the acquisition of mature commercial products and the procurement of emerging innovations. For new technologies, government institutions and state-owned enterprises may consider pre-commercial procurement, challenge-based contracts, pilot services, and outcome-based procurement. Under these arrangements, users purchase operational capabilities rather than simply acquiring vehicles.

For example, a procurement contract may specify seabed mapping over a defined area at a required quality level or inspection of a specified pipeline length. Service-based procurement can help domestic technology developers accumulate operating hours, reliability data, and recurring revenue without requiring end-users to assume the full risks associated with early product ownership. Domestic-content policies should be implemented progressively and assessed according to functional capabilities. During the initial phase, priorities may include system design, structural components, enclosures, wiring harnesses, software, integration, testing, and maintenance, repair, and overhaul (MRO) services. Components that are not yet economically feasible to manufacture domestically may continue to be imported, provided that national developers retain control over interfaces, data, documentation, and maintenance rights. During subsequent phases, strategically important components with sufficient production demand and economic potential, including thrusters, acoustic modems, connectors, pressure sensors, and battery modules, may be prioritized for domestic substitution.

Implementation Risks and Mitigation Strategies

A technology development roadmap may fail if it is implemented merely as a list of technological targets. Table 8 summarizes the principal implementation risks, potential failure mechanisms, mitigation strategies, and early warning indicators.Risk registers should be maintained and updated at both program and portfolio levels and should be directly linked to funding and continuation decisions.

Table 8. Roadmap implementation risks and mitigation strategies.

Risk	Failure mechanism	Principal mitigation strategy	Early warning indicators
Institutional fragmentation	Disconnected projects and facilities, duplication of equipment and data	Single program owner, national inventory, shared testing protocols	Duplicated expenditure, low facility utilization

Lisensi Creative Commons Atribusi 4.0 Internasional.

Risk	Failure mechanism	Principal mitigation strategy	Early warning indicators
Technology push	Features do not correspond to actual user requirements	CONOPS and acceptance criteria approved by off-takers from the beginning	Late requirement changes, passive end-user involvement
Prototype trap	Development stops after demonstrations without reliability growth	Repeated test–fix–test cycles, operating-hour targets, corrective-action closure	Repeated anomalies, incomplete documentation
Import lock-in	Proprietary interfaces and software prevent component substitution	Open architectures, ICDs, source-code escrow, data ownership	Dependence on one supplier, increasing licensing costs
Safety incidents	Battery, tether, recovery-system, or pressure-housing failures	Safety cases, defined operational envelopes, emergency and recovery plans	Unreported near misses, procedural bypasses
Human resource turnover	Critical knowledge is concentrated in individuals and lost when personnel leave	Configuration management, training pipelines, logbooks, communities of practice	Projects stop when key personnel depart
Absence of an initial market	Products fail to establish operational track records and secure contracts	First-buyer procurement and minimum pilot-service commitments	Unused prototypes, absence of repeat missions
Excessively ambitious targets	Deep-water or swarm systems pursued before reliability foundations are established	Phase gates and independent technical reviews	Technical milestones without supporting operational evidence

National Monitoring, Evaluation, and Data Management

Monitoring and evaluation should distinguish among inputs, outputs, outcomes, and impacts. Funding levels, equipment acquisitions, and scientific publications primarily represent program inputs or outputs. Outcomes refer to technologies that are actually deployed, accumulated operating hours, high-quality data production, competent personnel, and commercial contracts. Impacts include reduced dependence on imported technologies, stronger national control over marine data, improved operational safety, industrial growth, and contributions to marine science and the blue economy. Programs that produce numerous prototypes but fail to achieve repeated operational deployment should not be considered successful solely on the basis of academic outputs.

The development of a National Underwater Technology Observatory is therefore recommended. This initiative should function as a curated repository rather than a conventional information portal. The repository should maintain information on available facilities, testing capabilities, technological products, evidence-supported TRLs, qualified personnel, research projects, patents, technical standards, sea-trial data, failure and anomaly databases, and procurement opportunities. Sensitive information should be managed through appropriate access classifications and controls. Such a repository would enable government institutions to minimize duplicated investments, help industry identify technological partners, provide researchers with access to testing data, and allow assessors to evaluate documented operational performance. Ten principal indicators are recommended for monitoring national capability development:

1. Number of requirements originating from off-takers.
2. Number of technologies successfully passing decision gates with complete evidence packages.
3. Cumulative operating hours and mean time between critical failures.
4. Success rates for launch, mission execution, and recovery.
5. Data quality relative to mission-specific technical standards.
6. Domestic value creation and MRO capabilities.
7. Number of technically competent personnel.
8. Number of certified technological products.
9. Number of contracts and repeat orders.
10. Export value or import substitution achieved.

Strategic Implications

The central finding of this study is that technological independence should not be understood as a binary distinction between imported and domestically manufactured equipment. Instead, national technological independence refers to the capability to define requirements, control system architectures and interfaces, evaluate risks, generate performance evidence, operate and maintain equipment, implement modifications, and develop subsequent technology generations. During the initial development phases, the use of imported components may remain economically and technically reasonable, provided that it does not create long-term technological lock-in and contributes to the development of domestic systems engineering capabilities. A realistic technological catch-up strategy should prioritize specialized mission areas with strong domestic demand. Observation-class ROVs, coastal mapping AUVs, environmental gliders,

Lisensi Creative Commons Atribusi 4.0 Internasional.

inspection payloads, and acoustic monitoring systems represent more practical entry points than immediately pursuing fully integrated ultra-deep-water systems.

Operating hours and technical data generated through these applications can progressively establish a culture of reliability, strengthen domestic supply chains, develop professional competencies, and increase end-user confidence. Once the foundational capability stack has matured, technological systems can be extended toward deeper-water and more operationally complex missions. Emerging international standards addressing AUV risk and reliability and seabed mapping using unmanned marine vehicles [13], [14] provide opportunities for Indonesia to establish qualification pathways from the earliest stages of technology development rather than introducing them only after product completion. These developments also create opportunities for participation in international standardization activities. Indonesia could contribute technical experience gained from tropical marine environments, archipelagic operating conditions, complex currents, high turbidity, biofouling, and remote-area logistics to international standardization forums.

Participation in the development of technical standards represents an important dimension of technological sovereignty because standards influence how system performance, operational reliability, and safety requirements are defined and evaluated. Finally, the national roadmap should be integrated with marine science development and the blue economy agenda. Testing infrastructure and underwater vehicles initially developed for industrial applications can also contribute to oceanographic data collection, bathymetric surveys, habitat mapping, and environmental monitoring, provided that appropriate data governance arrangements are established from the beginning. Such integration would support the development of marine scientific capacity, as emphasized by UNESCO-IOC [8], [9], while expanding the potential user base and business opportunities for domestically developed underwater technologies.

POLICY RECOMMENDATIONS

A National Underwater Technology Program should be established as a mission-oriented initiative with a designated program owner, technical authority, and independent evaluation mechanism. Program responsibilities should be organized according to capability stacks and intended mission outcomes rather than institutional boundaries. This organizational arrangement would help establish clearer accountability, reduce fragmented investments, and strengthen coordination among research institutions, industry, government agencies, and end-users. As an initial measure, a comprehensive national capability audit should be conducted during 2026–2027 to identify existing testing facilities, equipment, technological products, qualified personnel, research projects, patents, industrial contracts, technical standards, and operational data. The findings of this audit should establish a periodically updated national baseline capable of documenting changes in underwater technological capabilities over time.

Testing infrastructure should be strengthened through the establishment of a distributed national test network integrating pressure chambers, towing tanks, maneuvering basins, calibration laboratories, hardware-in-the-loop facilities, sea-trial corridors, and data repositories. These facilities should operate under harmonized procedures, standardized documentation requirements, and consistent evidence formats to support reproducible technology qualification. Subsequent product development should adopt staged assurance and phase-gate procurement mechanisms. Operational approval should be granted for clearly defined operating envelopes only after developers provide adequate evidence of design compliance, testing outcomes, reliability growth, operator competence, and recovery preparedness. To accelerate technological commercialization, at least two first-buyer programs should be established for observation-class ROVs and coastal mapping AUVs through pilot-service or outcome-based procurement arrangements. These mechanisms would allow domestic products to accumulate operational experience, performance records, and user feedback before entering broader commercial markets.

Technological development should also be supported by a national competency framework covering system engineers, pressure engineers, navigation and control engineers, ROV/AUV operators, technicians, hydrographic data specialists, and assurance assessors. Education and training programs should emphasize the development of verifiable engineering evidence rather than focusing exclusively on prototype fabrication. All publicly funded technology development projects should incorporate requirements for open system architectures, interface control, data ownership, configuration management, and cybersecurity. These provisions are important for reducing vendor lock-in, preserving maintenance and modification capabilities, and supporting long-term technological sustainability. Ultimately, program success should be evaluated according to demonstrated outcomes and impacts, including reliability, availability, data quality, the number of certified products, domestic value creation, completed operational missions, repeat orders, and export readiness. These indicators provide a more meaningful basis for assessing national technological progress than the number of scientific publications, prototypes, or coordination activities alone.

CONCLUSION

Strengthening Indonesia's national capacity in underwater technology requires a fundamental paradigm shift from prototype-oriented development toward the establishment of an integrated technological capability system. The principal capability gaps extend beyond underwater vehicles and individual components to encompass the interconnections among mission requirements, system architectures, testing infrastructure, standardization, certification, human resource competencies, supply chains, procurement mechanisms, and lifecycle support. These elements must function as an

Lisensi Creative Commons Atribusi 4.0 Internasional.

interconnected ecosystem to ensure that technological development progresses beyond experimental demonstrations toward reliable operational deployment. Without a comprehensive and traceable body of engineering evidence, domestically developed underwater technologies may struggle to gain end-user confidence and achieve commercial or institutional acceptance, even when initial prototype demonstrations are successful.

An effective Triple Helix innovation model should be operationalized through a structured *program partnership* that establishes clearly defined responsibilities among participating stakeholders. Universities and research institutions should contribute scientific knowledge, technological innovation, and verifiable engineering evidence, while industrial partners should undertake system integration, manufacturing, maintenance, and lifecycle support. Government institutions should establish national mission priorities, provide sustainable funding and shared testing infrastructure, develop technical standards, and facilitate procurement pathways. Meanwhile, off-takers should contribute actual operational requirements, acceptance criteria, and opportunities for initial market adoption. This collaborative arrangement requires a designated program owner, transparent decision gates, and evidence-based evaluation mechanisms to strengthen accountability and ensure continuity throughout the technology development process.

The proposed national underwater technology roadmap for 2026–2045 consists of four progressive phases: foundation development, system integration, industrial scaling, and technological leadership. Progression between phases should be evaluated using evidence-supported Technology Readiness Levels (TRLs), system reliability, operating hours without critical failures, data quality, maintenance, repair, and overhaul (MRO) capabilities, domestic value creation, personnel competencies, certification status, industrial contracts, and repeat orders. By adopting realistic development priorities—beginning with observation-class ROVs, coastal mapping AUVs, testing facilities, navigation and communication technologies, and first-buyer procurement mechanisms—Indonesia can progressively strengthen its technological independence while developing a more reliable and sustainable underwater technology ecosystem. Ultimately, the proposed framework provides a strategic foundation for advancing national capabilities in marine science, the blue economy, operational safety, and maritime sovereignty toward 2045.

REFERENCES

[1] Republik Indonesia, Undang-Undang Republik Indonesia Nomor 32 Tahun 2014 tentang Kelautan, Jakarta, Indonesia, 2014.

[2] Republik Indonesia, Peraturan Presiden Republik Indonesia Nomor 16 Tahun 2017 tentang Kebijakan Kelautan Indonesia, Jakarta, Indonesia, 2017.

[3] Republik Indonesia, Peraturan Presiden Republik Indonesia Nomor 34 Tahun 2022 tentang Rencana Aksi Kebijakan Kelautan Indonesia Tahun 2021–2025, Jakarta, Indonesia, 2022.

[4] Republik Indonesia, Undang-Undang Republik Indonesia Nomor 59 Tahun 2024 tentang Rencana Pembangunan Jangka Panjang Nasional Tahun 2025–2045, Jakarta, Indonesia, 2024.

[5] Republik Indonesia, Peraturan Presiden Republik Indonesia Nomor 12 Tahun 2025 tentang Rencana Pembangunan Jangka Menengah Nasional Tahun 2025–2029, Jakarta, Indonesia, 2025.

[6] Republik Indonesia, Peraturan Presiden Republik Indonesia Nomor 38 Tahun 2018 tentang Rencana Induk Riset Nasional Tahun 2017–2045, Jakarta, Indonesia, 2018.

[7] Republik Indonesia, Undang-Undang Republik Indonesia Nomor 11 Tahun 2019 tentang Sistem Nasional Ilmu Pengetahuan dan Teknologi, Jakarta, Indonesia, 2019.

[8] Intergovernmental Oceanographic Commission of UNESCO, Global Ocean Science Report 2020: Charting Capacity for Ocean Sustainability. Paris, France: UNESCO Publishing, 2020.

[9] Intergovernmental Oceanographic Commission of UNESCO, The Science We Need for the Ocean We Want: United Nations Decade of Ocean Science for Sustainable Development (2021–2030) Implementation Plan. Paris, France: UNESCO, 2021.

[10] H. Etzkowitz and L. Leydesdorff, “The dynamics of innovation: From national systems and ‘Mode 2’ to a Triple Helix of university–industry–government relations,” Research Policy, vol. 29, no. 2, pp. 109–123, 2000, doi: 10.1016/S0048-7333(99)00055-4.

[11] Organisation for Economic Co-operation and Development, Commercialising Public Research: New Trends and Strategies. Paris, France: OECD Publishing, 2013, doi: 10.1787/9789264193321-en.

[12] International Organization for Standardization, ISO 16290:2013, Space Systems—Definition of the Technology Readiness Levels (TRLs) and Their Criteria of Assessment. Geneva, Switzerland: ISO, 2013.

[13] International Organization for Standardization, ISO 20682:2026, Autonomous Underwater Vehicles—Risk and Reliability. Geneva, Switzerland: ISO, 2026.

[14] International Organization for Standardization, ISO 25451:2026, Ships and Marine Technology—Technical Requirements and Guidelines for Seafloor Mapping with Uncrewed Marine Vehicles. Geneva, Switzerland: ISO, 2026.

[15] DNV, “Unmanned underwater vehicles—Classification, certification and testing services,” DNV, Høvik,

Lisensi Creative Commons Atribusi 4.0 Internasional.

Norway, 2026. [Online]. Available: https://www.dnv.com/services/maritime-certification-materials-components/underwater-technology-services-1751/unmanned-underwater-vehicles-1710/. Accessed: Aug. 2, 2026.
[16] International Hydrographic Organization, IHO Standards for Hydrographic Surveys, S-44, 6th ed. Monaco: IHO, 2022.
[17] J. Yuh, "Design and control of autonomous underwater robots: A survey," Autonomous Robots, vol. 8, no. 1, pp. 7–24, 2000, doi: 10.1023/A:1008984701078.
[18] T. I. Fossen, Handbook of Marine Craft Hydrodynamics and Motion Control, 2nd ed. Hoboken, NJ, USA: Wiley, 2021.
A. Sahoo, S. K. Dwivedy, and P. S. Robi, "Advancements in the field of autonomous underwater vehicle," Ocean Engineering, vol. 181, pp. 145–160, 2019, doi: 10.1016/j.oceaneng.2019.04.011.
B. Zhang, D. Ji, S. Liu, X. Zhu, and W. Xu, "Autonomous underwater vehicle navigation: A review," Ocean Engineering, vol. 273, Art. no. 113861, 2023, doi: 10.1016/j.oceaneng.2023.113861.
C. Alexandris, P. Papageorgas, and D. Piromalis, "Positioning systems for unmanned underwater vehicles: A comprehensive review," Applied Sciences, vol. 14, no. 21, Art. no. 9671, 2024, doi: 10.3390/app14219671.
[19] F. F. R. Merveille, B. Jia, Z. Xu, and B. Fred, "Advancements in sensor fusion for underwater SLAM: A review on enhanced navigation and environmental perception," Sensors, vol. 24, no. 23, Art. no. 7490, 2024, doi: 10.3390/s24237490.
[20] F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," Ad Hoc Networks, vol. 3, no. 3, pp. 257–279, 2005, doi: 10.1016/j.adhoc.2005.01.004.
[21] N. Saeed, A. Çelik, T. Y. Al-Naffouri, and M.-S. Alouini, "Underwater optical wireless communications, networking, and localization: A survey," Ad Hoc Networks, vol. 94, Art. no. 101935, 2019, doi: 10.1016/j.adhoc.2019.101935.
[22] X. Chen, N. Bose, M. Brito, F. Khan, B. Thanyamanta, and T. Zou, "A review of risk analysis research for the operations of autonomous underwater vehicles," Reliability Engineering & System Safety, vol. 216, Art. no. 108011, 2021, doi: 10.1016/j.ress.2021.108011.
[23] Liu, F. Yu, B. He, and C. G. Soares, "A review of underwater docking and charging technology for autonomous vehicles," Ocean Engineering, vol. 297, Art. no. 117154, 2024, doi: 10.1016/j.oceaneng.2024.117154.
[24] M. Brito and G. Griffiths, "A Bayesian approach for predicting risk of autonomous underwater vehicle loss during their missions," Reliability Engineering & System Safety, vol. 146, pp. 55–67, 2016, doi: 10.1016/j.ress.2015.10.004.
[25] C. A. Thieme and I. B. Utne, "Safety performance monitoring of autonomous marine systems," Reliability Engineering & System Safety, vol. 159, pp. 264–275, 2017, doi: 10.1016/j.ress.2016.11.024.
[26] S. B. Williams and I. Mahon, "Simultaneous localisation and mapping on the Great Barrier Reef," IEEE Robotics & Automation Magazine, vol. 11, no. 3, pp. 37–46, Sep. 2004, doi: 10.1109/MRA.2004.1337824.
[27] B. Jalving, K. Gade, O. K. Hagen, and K. Vestgård, "A toolbox of aiding techniques for the HUGIN AUV integrated inertial navigation system," in Proc. OCEANS 2003, San Diego, CA, USA, 2003, pp. 1146–1153, doi: 10.1109/OCEANS.2003.178456.
[28] International Maritime Organization, Revised Guidelines for Formal Safety Assessment (FSA) for Use in the IMO Rule-Making Process, MSC-MEPC.2/Circ.12/Rev.2. London, U.K.: IMO, 2018.
[29] Biro Klasifikasi Indonesia, Rules for Approval of Manufacturers and Service Suppliers. Jakarta, Indonesia: BKI, 2024.

Lisensi Creative Commons Atribusi 4.0 Internasional.