The Future of Underwater Technology in Indonesia: Strategic Priorities, Capability Gaps, and an Innovation Roadmap for the Global Ocean Economy

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Abstract

Underwater technology is strategic infrastructure connecting the blue economy, ocean science, offshore energy, submarine-cable resilience, environmental protection, and maritime security. This perspective paper reframes Indonesia's underwater-technology agenda through a structured literature synthesis, capability-gap analysis, value-chain mapping, and a proposed 2026–2045 roadmap. The analysis indicates that the central challenge is not merely the limited number of domestic vehicle prototypes. More consequential constraints include dependence on critical imported components, fragmented test facilities, unclear certification pathways, discontinuous research funding, limited mission software and data infrastructure, and the absence of reliable first markets for domestic systems. Near-term priorities should therefore emphasize inspection and mapping services, observation-class remotely operated vehicles, oceanographic sensors, control software, system integration, calibration, maintenance, and lifecycle support. These capabilities can subsequently be extended toward shallow-water autonomous underwater vehicles, acoustic modems, persistent observing systems, and deep-water platforms. The paper proposes a national mission ecosystem linking universities and BRIN, industry, government, regulators, and end users through shared infrastructure, open interfaces, performance-based procurement, and a stage-gate mechanism from research to commercialization. A four-phase roadmap positions Indonesia first as an effective operator and integrator, then as a manufacturer of certified systems, and ultimately as a regional provider of underwater products and lifecycle services by 2045. Progress should be assessed using operational reliability, meaningful local content, certified-system counts, accumulated sea hours, lifecycle cost, and export growth rather than prototype counts alone.

Keywords: underwater technology, blue economy, AUV, ROV, technological independence, submarine cables, innovation roadmap

INTRODUCTION

Indonesia's geography makes the ocean not only a natural resource base but also the physical medium that connects islands, energy systems, logistics corridors, digital infrastructure, and national security. The global ocean economy is expected to expand as demand grows for offshore energy, marine food, seabed information, climate services, digital connectivity, and ecosystem restoration. The OECD and the World Bank consequently frame ocean development as an economic opportunity that must remain compatible with environmental sustainability and social inclusion [3], [4]. For Indonesia, this framing is particularly important because the benefits of maritime growth depend on the ability to observe, inspect, maintain, and govern an exceptionally large and diverse marine domain.

Underwater technology provides the operational layer for these activities. It includes remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), gliders, seabed landers, acoustic networks, imaging systems, environmental sensors, positioning and navigation systems, subsea power and communication links, and the software used to plan missions and interpret data [1], [5], [6]. These systems reduce the need for divers in hazardous environments, expand the duration and spatial coverage of surveys, and enable repeatable measurements at depths and in conditions that are difficult for conventional vessels. Their importance is demonstrated by applications in deep-ocean science, bathymetric mapping, habitat monitoring, offshore inspection, spill response, and critical-infrastructure protection [7], [11], [12], [15]–[18].

The strategic significance of these technologies is increasing. Submarine cables carry nearly all international digital traffic and are vulnerable to anchors, fishing activity, geohazards, repair delays, and deliberate interference [2], [20], [24]. Offshore energy and marine-resource development require increasingly capable inspection and monitoring systems. Climate adaptation and disaster-risk reduction depend on better ocean observations. Maritime security requires persistent awareness below the surface, where conventional satellite and radar systems have limited reach. In each of these domains, countries that control mission data, system architecture, maintenance, and critical components possess greater operational autonomy than countries that only purchase complete foreign systems.

Indonesia has demonstrated research capability through university and government prototypes, but technological independence cannot be measured by prototype completion alone. A sustainable capability requires repeatable manufacturing, documented reliability, interoperable software, calibration, sea-trial evidence, certification, trained operators, spare parts, and lifecycle support. It also requires an industrial customer willing to adopt domestic systems. The original article correctly identified import dependence, weak technology transfer, low research investment, and limited human-resource capacity as key barriers. This revision extends that argument by distinguishing between operational capability, integration capability, design authority, component manufacturing, certification, and commercial scale.

The objective of this paper is therefore to develop a more actionable perspective on the future of underwater technology in Indonesia. It first defines the technology landscape and its strategic functions, then examines capability gaps and industrial opportunities, and finally proposes a phased national roadmap to 2045. The central proposition is that Indonesia should not attempt to localize every high-end system simultaneously. A mission-driven portfolio should begin with services and components that generate operational learning and recurring demand, then progress toward integrated vehicles and persistent ocean-observation networks. This approach is consistent with international guidance on ocean-science capacity and transfer of marine technology [21], [25] and with Indonesia's blue-economy policy direction [22], [23].

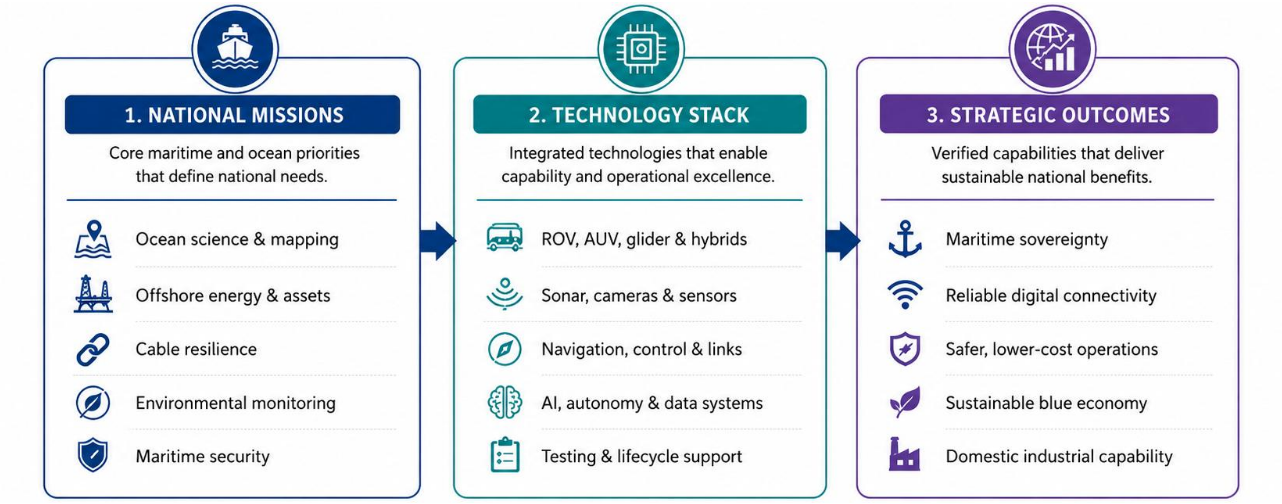

Figure 1. Integrated architecture linking national missions, underwater-technology capabilities, and strategic outcomes.

ANALYTICAL SCOPE AND METHOD

This study is a perspective and strategic-analysis paper rather than an experimental vehicle-design study. The analysis uses a structured narrative review of peer-reviewed literature, international policy documents, and established technology references. The evidence base covers underwater robotics, vehicle navigation, acoustic communication, optical imaging, environmental monitoring, ocean science capacity, submarine-cable policy, and blue-economy development. Seminal sources are retained where they define enduring technical principles, while policy and institutional sources are used to frame current strategic needs [1]–[30].

The analytical process consists of four steps. First, underwater technology is decomposed into platforms, payloads, enabling subsystems, data infrastructure, test and certification, and lifecycle services. Second, strategic missions are mapped to the capabilities required to execute them. Third, a capability-gap assessment compares the functions Indonesia must control with the typical position of a technology-importing user. Fourth, priorities are organized into a phased roadmap using five criteria: national importance, demand visibility, technical attainability, opportunity for domestic value creation, and potential for regional export.

The roadmap does not claim to predict specific procurement volumes or market values. It is a decision framework for sequencing capability development. Technology readiness level (TRL) is treated as necessary but insufficient because a prototype can reach a high laboratory TRL without possessing manufacturing readiness, regulatory acceptance, field reliability, cybersecurity, or a viable service organization. Accordingly, each roadmap phase includes operational evidence and institutional milestones in addition to technical outputs.

Table 1. Underwater-technology system decomposition used in this study

Layer	Representative elements	Primary national capability question
Mission platforms	ROV, AUV, glider, lander, hybrid vehicle, USV relay	Can the system complete a defined mission safely and repeatedly?

Payloads and sensors	Multibeam/side-scan sonar, camera, CTD, chemical and biological sensors	Can sensors be calibrated, integrated, and interpreted locally?
Navigation and control	INS, DVL, USBL/LBL, SLAM, guidance, autonomy	Who controls algorithms, interfaces, updates, and failure responses?
Communication and power	Acoustic modem, optical link, cable, battery, pressure-tolerant electronics	Which critical components remain single-source imports?
Data and digital layer	Mission planning, edge AI, geospatial database, digital twin, cybersecurity	Can Indonesia own, secure, reuse, and standardize mission data?
Testing and assurance	Pressure testing, tank trials, calibration, EMC, sea trials, reliability	Is evidence sufficient for certification and end-user acceptance?
Lifecycle services	Maintenance, spares, repair, upgrades, operator training	Can availability be sustained at predictable lifecycle cost?

UNDERWATER TECHNOLOGY AS STRATEGIC INFRASTRUCTURE

Ocean Science, Mapping, and Environmental Intelligence

Ocean governance begins with reliable observations. AUVs and gliders can collect bathymetric, physical, chemical, and biological data with higher spatial consistency than many ship-only surveys. Photomosaicking, terrain mapping, and object-based image analysis support habitat assessment, archaeological documentation, infrastructure inspection, and change detection [7], [16], [17], [18]. Environmental robots have also demonstrated value in tracking pollutant plumes and monitoring hazardous events where repeated human sampling is difficult [11], [12].

Indonesia's need is not limited to acquiring more vehicles. It requires a national observation architecture in which mission plans, sensor calibration, metadata, quality control, and long-term data stewardship are standardized. UNESCO's assessment of global ocean-science capacity highlights the importance of infrastructure, technical personnel, data systems, and sustained investment rather than isolated research campaigns [21]. The Second World Ocean Assessment similarly emphasizes that management decisions depend on integrated, repeatable, and accessible ocean observations [26]. A domestic underwater-technology program should therefore be linked to national hydrography, fisheries management, marine spatial planning, disaster monitoring, and conservation priorities.

Offshore Energy and Subsea Asset Integrity

Offshore oil and gas facilities, subsea pipelines, cables, risers, mooring systems, and future marine-renewable installations require inspection throughout their lifecycle. ROVs remain important where real-time human supervision and intervention are necessary, while AUVs are increasingly used for wide-area surveys and repeatable inspection. Advances in autonomy, navigation, and imaging allow vehicles to follow structures, detect anomalies, and build georeferenced condition records [5], [6], [8], [10].

This mission area offers an attractive entry point for Indonesian industrialization because the value proposition is operational: reduced vessel time, lower diver exposure, faster inspection, and better asset data. Domestic companies can enter through survey services, vehicle operation, sensor integration, reporting software, and maintenance before attempting full production of work-class ROVs. Repeated service contracts create sea hours, failure data, and user feedback—evidence that laboratory projects normally lack. The same capabilities can later support offshore wind, ocean-current energy, aquaculture infrastructure, and port inspection.

Submarine-Cable Resilience and Digital Sovereignty

Submarine fiber-optic cables are the physical backbone of international connectivity [2], [20]. Their resilience is now treated as a global policy issue because faults can disrupt financial services, public administration, education, healthcare, and cloud infrastructure. International initiatives emphasize route diversity, risk reduction, timely repair, information sharing, and coordination between governments and cable operators [24]. For an archipelagic state, domestic inter-island cables are also essential to equitable digital access.

Underwater technology contributes at four stages: route survey, burial and installation support, periodic inspection, and incident response. A national capability should combine geophysical survey, anomaly detection, seabed-change monitoring, cable-location databases, risk maps, and rapid-deployment inspection vehicles. Strategic autonomy does not necessarily require domestic manufacture of every deep-sea cable system. It does require control of cable-location data, trained inspection teams, mission-ready platforms, and the ability to support repair decisions without waiting for foreign mobilization.

Maritime Security and Critical-Infrastructure Protection

The underwater domain is difficult to observe continuously. Sonar, passive acoustic arrays, mobile AUVs, seabed nodes, and data-fusion systems can extend awareness beyond the coverage of surface sensors. Underwater autonomy has advanced from simple waypoint following toward nested mission behaviors, adaptive sampling, and cooperative operations [1], [10], [19]. These technologies can support port security, mine-countermeasure research, monitoring of restricted zones, and protection of energy and communication infrastructure.

Security applications require stronger governance than civilian survey missions. Systems need cybersecurity, access control, secure communications, configuration management, and clear data classification. Dual-use risks also mean that research openness must be balanced with safeguards. A national program should separate generic enabling research—such as navigation, materials, power, and reliability—from mission-specific operational capabilities. This allows universities and industry to innovate while sensitive deployment concepts remain under appropriate authority.

Table 2. Strategic mission areas and their enabling underwater technologies

Mission area	Required technology set	Near-term Indonesian opportunity
Seabed mapping and ocean science	AUV/glider, multibeam sonar, navigation, sensor calibration, data portal	Standardized coastal and shelf survey services
Offshore asset integrity	ROV/AUV, imaging sonar, visual analytics, manipulator, inspection database	Recurring inspection, maintenance, and anomaly-reporting services
Submarine-cable resilience	Route survey, buried-cable detection, seabed-change analysis, rapid response	National cable-risk maps and domestic inspection teams
Environmental monitoring	Gliders, landers, water-quality sensors, adaptive sampling, cloud data	Persistent monitoring around ports, aquaculture, and protected areas
Disaster and emergency response	Rapid-deployment ROV/AUV, sonar search, plume tracking	Search, damage assessment, spill and hazard response
Maritime security	Passive/active acoustics, autonomous patrol, secure communication, fusion	Protection of selected ports and critical subsea infrastructure

TECHNOLOGY LANDSCAPE AND FUTURE DIRECTIONS

Platforms: ROVs, AUVs, Gliders, and Cooperative Fleets

ROVs provide tethered power, high-bandwidth communication, and direct operator control, while the guidance-and-control framework described by Fossen remains foundational for marine vehicle modelling [9]. They are therefore preferred for intervention, close visual inspection, and tasks involving manipulators. Their limitations are vessel dependence, tether management, and mobilization cost. AUVs remove the tether and can survey large areas efficiently, but must manage finite energy, uncertain navigation, limited communication, and autonomous fault response. Hybrid vehicles combine aspects of both approaches, while gliders trade speed and payload power for very long endurance [5], [6], [15], [28].

The future is likely to involve heterogeneous fleets rather than a single universal vehicle. A surface or aerial relay can support multiple underwater vehicles; a large AUV can deploy smaller sensors; and seabed nodes can provide localization and communication. Cooperative autonomy can distribute tasks across platforms, but it also increases the need for standard interfaces, mission assurance, and common data formats. Indonesia should therefore prioritize modular architecture and payload interchangeability rather than developing isolated prototypes with proprietary interfaces.

Navigation, Communication, and Underwater Perception

Satellite navigation is generally unavailable below the surface, so underwater vehicles rely on inertial navigation, Doppler velocity logs, acoustic positioning, terrain-aided navigation, and simultaneous localization and mapping. The HUGIN navigation architecture and subsequent research demonstrate the benefit of combining multiple aiding sources to limit position drift [8]. Bathymetric and visual mapping algorithms further improve localization when the environment provides recognizable terrain or features [16], [18].

Communication is constrained by the physics of the underwater channel. Radio is strongly attenuated in seawater, optical links require short range and clear water, and acoustic communication offers long range but limited bandwidth, high latency, multipath, and variable reliability [14], [29], [30]. These constraints shape system design: autonomous vehicles must make many decisions locally, record high-volume data onboard, and transmit only essential status or low-rate information. Domestic capability in acoustic modems, networking protocols, and mission software is therefore strategically valuable because these subsystems determine fleet coordination and operational independence.

Artificial Intelligence, Edge Processing, and Digital Twins

Artificial intelligence can improve target detection, image enhancement, adaptive route planning, anomaly classification, and energy management. Optical-system performance must still account for water attenuation, scattering, lighting geometry, and camera configuration [13]. Yet AI performance is only as credible as the training data and validation regime. Underwater imagery varies with turbidity, lighting, biofouling, altitude, and sensor configuration; sonar interpretation also depends on frequency, geometry, and seabed type. Models trained on foreign datasets may not generalize to Indonesian waters. A national program should build curated, labelled datasets from representative tropical, turbid, reef, port, and deep-water environments.

Figure 2. Capability-development ladder from technology operation to regional export.

Digital twins can connect vehicle configuration, mission history, sensor health, maintenance records, and environmental conditions. Their practical value is predictive maintenance and evidence-based lifecycle management rather than visualization alone. For domestic manufacturers, a digital thread from design to sea trial and maintenance can improve traceability and certification. For operators, it can reduce downtime and provide an auditable record of system performance.

INDONESIA'S CAPABILITY GAP

Indonesia's current position is heterogeneous. Universities and research institutions can design hulls, implement basic control algorithms, integrate commercial sensors, and demonstrate prototypes. Service companies can operate imported ROV and survey systems. State-owned and private industries possess capabilities in shipbuilding, electronics, defense integration, and telecommunications. However, these capabilities are not yet organized as a continuous national value chain.

The first gap is in critical components. Pressure-tolerant connectors, reliable thrusters, high-energy-density batteries, precision inertial sensors, Doppler velocity logs, acoustic modems, imaging sonar, and deep-rated housing are commonly imported. Import dependence is not inherently inefficient when production volumes are small, but it becomes strategic when a component is subject to long lead times, export restrictions, proprietary software, or unavailable repair support. Localization priorities should therefore be based on supply risk and lifecycle value, not only on component price.

The second gap is verification infrastructure. An underwater vehicle may perform well in a campus pool but fail due to leaks, corrosion, electromagnetic interference, navigation drift, thermal problems, connector damage, software resets, or biofouling during sustained marine operation. Pressure chambers, towing and maneuvering facilities, acoustic calibration ranges, controlled coastal test sites, and instrumented sea trials are essential. Shared national facilities are more efficient than duplicating expensive infrastructure in many institutions [21].

The third gap is certification and acceptance. End users require evidence that systems meet mission, safety, reliability, and data-security requirements. Domestic standards should not simply reproduce foreign class rules; they should define a transparent pathway from component testing through integrated system verification and operational acceptance. The IOC transfer-of-marine-technology framework stresses the importance of skills, knowledge, infrastructure, and institutional capacity rather than hardware transfer alone [25].

The fourth gap is the transition from research to market. Research funding often ends when a prototype is completed, whereas commercialization begins with design stabilization, documentation, reliability growth, manufacturability, service planning, and customer trials. Without first procurement, even technically sound systems cannot accumulate operational evidence. A performance-based government or BUMN procurement mechanism is therefore required for selected missions where domestic learning has strategic value.

The fifth gap concerns people. Underwater technology requires multidisciplinary teams: naval architecture, ocean engineering, mechanical design, embedded electronics, control, robotics, underwater acoustics, software, data science, hydrography, corrosion, materials, operations, and safety. Education should combine theory with field deployment, failure analysis, configuration control, and maintenance. Professional pathways are needed not only for researchers but also for technicians, pilots, mission planners, quality engineers, and data analysts.

Table 3. Capability-gap assessment for Indonesia

Capability dimension	Observed structural gap	Strategic response
Mission definition	Projects often begin with available technology rather than a funded user need	Mission-based programs with accountable end users
Critical components	Dependence on imported thrusters, navigation, sonar, connectors, and modems	Selective localization based on supply risk and lifecycle value
System integration	Prototype interfaces vary across institutions	Open payload, data, power, and software interfaces
Testing	Fragmented pool trials with limited pressure and endurance evidence	Shared pressure, acoustic, tank, and coastal test infrastructure
Certification	Unclear pathway from prototype to accepted operational system	National verification protocol aligned with class and user requirements
Data/software	Mission data and software are not consistently archived or reusable	National underwater-data standards, repositories, and configuration control
Industrial demand	Few repeatable first-customer contracts	Performance-based procurement and service contracts
Human resources	Shortage of multidisciplinary field-ready teams	Competency standards, apprenticeships, and sea-time requirements

INDUSTRIAL OPPORTUNITIES AND PRIORITIZATION

Service-First Industrialization

A service-first pathway reduces the risk of premature manufacturing investment. Inspection, mapping, monitoring, calibration, data processing, and maintenance generate revenue while building mission knowledge. Operators learn which failures matter, which components dominate downtime, and which interfaces users require. This operational evidence should guide product design. The approach also allows Indonesian companies to combine imported high-end components with domestic software, structures, mission planning, and support, gradually increasing local value without compromising service reliability.

The near-term market is broader than deep-ocean exploration. Ports require quay-wall and seabed inspection; aquaculture operators need net and mooring inspection; coastal governments need bathymetry and environmental monitoring; universities need affordable observation platforms; energy companies need pipeline and cable surveys; and disaster agencies need search and assessment capability. A modular observation-class ROV, standardized sensor pods, and a national mission-data platform could serve several of these markets.

Priority Technology Portfolio

Priority selection should balance sovereignty and feasibility. Technologies with high strategic importance but very high entry barriers—such as deep-rated precision inertial systems or advanced multibeam sonar—may initially remain imported. Domestic effort can focus on integration, software, ruggedized enclosures, power distribution, mission computers, simple sensors, cable-management systems, and maintenance. Over time, local production can move toward thrusters, acoustic modems, pressure-tolerant electronics, and complete shallow-water vehicles.

A portfolio is preferable to a single flagship program. Flagship systems attract attention but may fail to build supply chains if they are not connected to smaller recurring products. The proposed portfolio therefore includes: (1) observation-class ROVs; (2) shallow-water survey AUVs; (3) oceanographic and infrastructure sensor modules; (4) mission-planning and data software; (5) acoustic communication; (6) cable and subsea inspection services; and (7) shared testing and certification services.

Table 4. Proposed priority portfolio for 2026–2035

Priority	Rationale	Indicative first users	2035 target state
Observation-class ROV	High demand, manageable depth, strong training and service value	Ports, aquaculture, universities, emergency agencies	Certified domestic platform with interchangeable payloads
Shallow-water survey AUV	Builds autonomy, navigation, and mapping capability	Hydrography, coastal planning, energy and telecom	Operational 200–500 m class with domestic mission software
Sensor and payload modules	Reusable across imported and domestic vehicles	Research, environment, offshore operators	Calibrated domestic modules with documented interfaces
Mission software and data platform	High local-value potential and lower manufacturing barrier	All vehicle and survey operators	Secure interoperable planning, logging, QA, and analytics
Acoustic modem and network	Strategic fleet enabler and persistent-observation component	Research, defense, environmental monitoring	Short/medium-range domestic modem and protocol stack
Inspection and lifecycle services	Creates recurring demand, sea hours, and failure data	Cable, energy, port, aquaculture	National service network with rapid response and spare support
Test and certification services	Removes commercialization bottleneck	Universities, startups, BUMN, regulators	Accredited shared facilities and accepted verification procedures

NATIONAL INNOVATION AND GOVERNANCE MODEL

The institutional challenge is coordination across organizations with different incentives. Universities are rewarded for publications and student outcomes; research agencies emphasize scientific programs; industry needs revenue and manageable risk; regulators require evidence; and operators prioritize availability and safety. A national mission should not erase these differences. It should connect them through defined responsibilities, shared infrastructure, stable funding, and measurable operational outcomes.

Universities and BRIN should lead foundational research, algorithms, materials, scientific payloads, and early prototypes. Industry should own product configuration, manufacturing, quality assurance, supply chains, maintenance, and warranty. Government should finance common infrastructure, establish standards, create first markets, and protect fair competition. End users should define mission requirements, provide trial sites, and participate in acceptance testing. The Triple Helix model becomes effective only when the user and regulator are explicitly integrated into the commercialization pathway.

Technology transfer must be structured around capability acquisition. A foreign partnership should include access to interface documentation, local integration, operator and maintainer training, repair authority, test methods, and a pathway for domestic component substitution. The UNESCO-IOC framework provides a useful principle: transfer includes knowledge, expertise, equipment, and organizational capacity [25]. Merely purchasing a complete system does not constitute meaningful transfer.

Procurement should be performance based. Instead of specifying a foreign brand or an unrealistic percentage of local content, the buyer should define mission duration, depth, navigation accuracy, data quality, weather limits, reliability, maintainability, cybersecurity, and lifecycle support. Domestic suppliers can then propose architectures that meet these outcomes. Local content should be measured in engineering authority, software ownership, repair capability, and recurring value not only in structural weight.

Financing, Standards, and Data Governance

Financing should combine competitive research grants, mission-oriented engineering contracts, and operational service procurement. Research grants are suitable for uncertain scientific questions, while engineering contracts should fund design maturation, documentation, reliability growth, and integration against an agreed requirement. Operational procurement should pay for delivered survey, inspection, or monitoring outcomes. Separating these instruments prevents research budgets from carrying the full cost of commercialization and makes accountability clearer.

Shared technical standards are equally important. A national interface profile should define payload mounting, power, data exchange, time synchronization, coordinate systems, metadata, and health reporting. Open interfaces reduce dependence on a single vehicle and allow universities and companies to specialize. Data governance should specify ownership, retention, security classification, licensing, and conditions for research reuse. Publicly funded environmental datasets should be discoverable where security and commercial restrictions permit, while sensitive cable, energy, and defense data require controlled access.

A multi-year budget is necessary because underwater systems improve through repeated deployments. Annual project cycles encourage teams to rebuild hardware instead of correcting failure modes. Funding reviews should therefore examine cumulative sea hours, unresolved defects, supply-chain risks, and user adoption. Programs that do not demonstrate progress at agreed gates should be stopped or redirected; successful systems should receive sustained support for certification and first production.

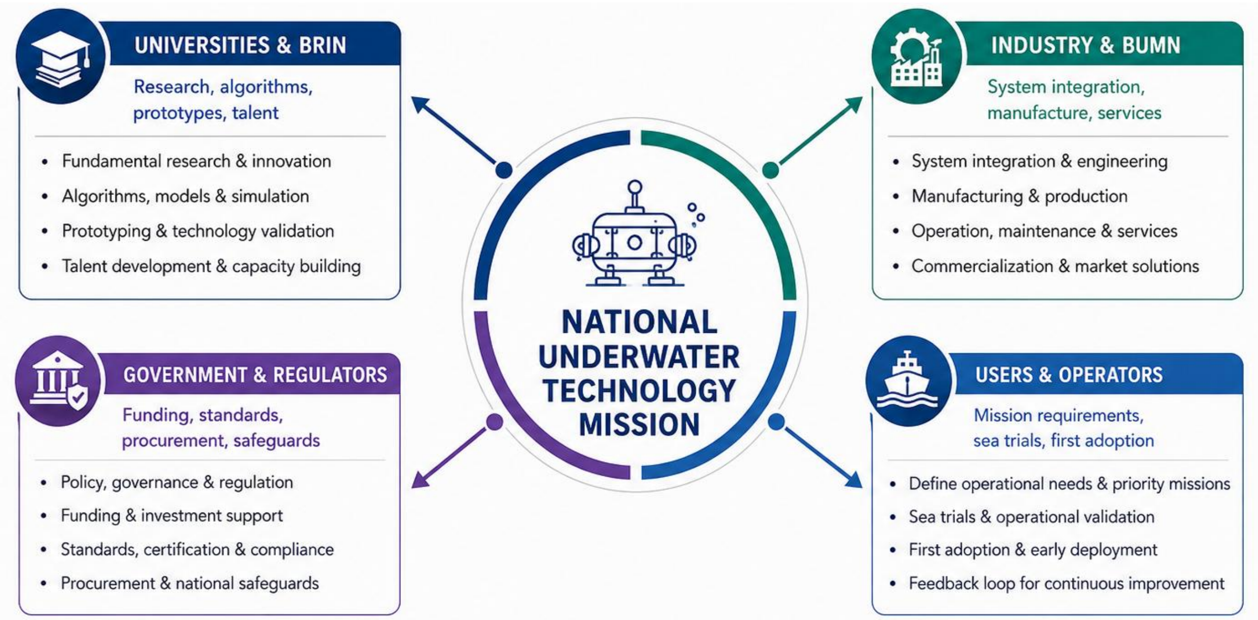

Figure 3. Proposed national mission ecosystem for underwater-technology development.

Table 5. Institutional responsibilities in a national underwater-technology mission

Actor	Core responsibility	Required deliverable
Universities and BRIN	Research, talent, algorithms, scientific validation	Documented prototypes, datasets, test methods, trained graduates
Industry and BUMN	Product ownership, manufacturing, integration, service	Configuration-controlled systems, quality records, spares and warranty
Government ministries	Mission funding, coordination, infrastructure, procurement	Multi-year program, shared facilities, performance-based tenders
Regulators and classification bodies	Safety, assurance, certification, data governance	Transparent verification and acceptance pathway
End users	Mission requirements, trial access, operational feedback	Use cases, acceptance criteria, sea-time commitment, first adoption
Telecom, energy, port and fisheries sectors	Recurring commercial demand	Service contracts and operational datasets
International partners	Specialized knowledge, components, joint validation	Transfer packages, interface access, training, local integration

ROADMAP 2026–2045

The proposed roadmap uses four phases. The dates are indicative and should be governed by gate reviews rather than calendar ambition. A phase should not be declared complete because a prototype exists; completion requires verified mission performance, documented reliability, trained personnel, supply support, and adoption by an operational user.

Phase I (2026–2030) establishes foundations. Priorities are a national mission office, capability inventory, shared pressure and coastal-test facilities, common data and payload interfaces, observation-class ROVs, sensor modules, maintenance capability, and a service-oriented procurement program. The target is to move from dispersed projects to repeatable operations.

Phase II (2031–2035) develops integrated domestic systems. Shallow-water AUVs, mission computers, autonomy software, acoustic communication, and locally maintainable propulsion and power modules become central. Certification procedures are exercised through real procurement. Universities and industry operate joint engineering teams, and field data are used for reliability growth.

Phase III (2036–2040) scales industry. The focus shifts to higher-end subsystems, work-class ROV components, persistent observation networks, cooperative autonomy, cable and subsea inspection services, and regional supply chains. Production quality, export compliance, cybersecurity, and lifecycle support become as important as technical performance.

Figure 4. Proposed four-phase roadmap for Indonesian underwater technology, 2026–2045.

Phase IV (2041–2045) targets regional leadership. Indonesia should be able to offer selected deep-water platforms, certified coastal and shelf systems, data services, and lifecycle support across Southeast Asia. Leadership does not require domestic production of every sensor. It requires control of system architecture, mission software, data, integration, maintenance, and customer relationships.

Table 6. Roadmap milestones and evidence of completion

Phase	Technical Milestones	Institutional and Market Milestones	Completion Evidence
2026–2030 Foundation	Observation ROV, modular payloads, data platform, pressure and sea-test capability	Mission office, shared facilities, competency framework, first service contracts	Multiple vehicles with >1,000 cumulative sea hours and documented reliability
2031–2035 Integration	Shallow-water AUV, domestic mission computer, acoustic modem, autonomy stack	Certification pathway, first operational procurement, domestic repair network	Certified system completing recurring user missions
2036–2040 Industrial Scale	Fleet autonomy, work-class subsystems, persistent observing nodes	Qualified suppliers, export compliance, regional service agreements	Repeat production with lifecycle availability and regional revenue
2041–2045 Regional Leadership	Selected deep-water systems, integrated networks, advanced analytics	ASEAN support hub, sustained R&D, international partnerships led by Indonesia	Exported products/services and recognized contribution to technical standards

STAGE-GATE COMMERCIALIZATION AND PERFORMANCE METRICS

A stage-gate pathway prevents research projects from being labelled commercial products prematurely. Gate 0 confirms a funded mission need and accountable user. Gate 1 approves the concept and system requirements. Gate 2 verifies a prototype in a controlled environment. Gate 3 validates subsystems under pressure, corrosion, endurance, and communication conditions. Gate 4 requires operational sea trials. Gate 5 addresses certification and safety evidence. Gate 6 is first procurement, and Gate 7 is repeat production and export.

At each gate, the evidence package should include requirements traceability, hazard analysis, verification procedures, software version control, test data, failure reports, corrective actions, maintenance plans, and lifecycle cost. This approach turns failures into institutional learning. It also allows government to stop weak projects early and concentrate resources on systems that demonstrate reliability and user value.

Performance metrics should shift away from counts of prototypes and publications. The central metrics are mission success, operational availability, mean time between failures, repair turnaround, navigation and data accuracy, cumulative sea hours, local engineering value, certified product families, recurring customers, and export revenue. Ocean-science outputs—open datasets, calibrated observations, and research use—should also be measured because public-interest missions may not generate direct commercial income [21], [27].

Figure 5. Stage-gate pathway for transforming research outputs into operational and commercial systems.

Table 7. Proposed national performance indicators

Indicator group	Examples	Why it matters
Operational performance	Mission success rate, sea hours, weather window, availability	Demonstrates usefulness beyond laboratory trials

Reliability and maintainability	MTBF, leak events, repair time, spare-part lead time	Determines lifecycle cost and user confidence
Technical quality	Navigation error, data completeness, sensor calibration, communication reliability	Connects system performance to mission outcomes
Industrial depth	Domestic design authority, software ownership, qualified suppliers, repair authority	Measures meaningful capability rather than assembly weight
Commercial adoption	Repeat customers, service contracts, first procurement, export revenue	Indicates sustainable demand and competitiveness
Human capital	Certified operators, engineers, technicians, apprenticeships, sea-time records	Builds the workforce needed for safe operations
Science and public value	Datasets, observing days, policy applications, disaster-response missions	Captures benefits not reflected in product sales

RISKS AND MITIGATION

A national underwater-technology strategy contains significant risks. The first is fragmentation: institutions may develop similar prototypes without common interfaces or shared testing. This can be mitigated through national architecture standards and competitive access to common facilities. The second risk is technology lock-in, where imported proprietary systems prevent local integration. Procurement should therefore require data ownership, interface access, and maintenance rights where strategically justified.

The third risk is overambition. Attempting an ultra-deep autonomous platform before establishing reliable shallow-water systems can produce expensive demonstrations with little operational value. The roadmap uses progressive depth, endurance, and autonomy targets. The fourth risk is weak demand. Government should not guarantee permanent protection for uncompetitive products, but it can create time-limited first markets tied to transparent performance targets.

The fifth risk is environmental and social harm. More underwater technology does not automatically produce a sustainable blue economy. Surveys and operations must manage acoustic disturbance, seabed contact, pollution, and data ethics. Environmental monitoring should be integrated into mission planning, and ocean development should remain aligned with ecosystem health and equitable benefits [4], [23], [26]. The sixth risk is security. Autonomous and connected systems require cybersecurity, controlled software updates, secure logs, and clear authority for sensitive missions.

Table 8. Major implementation risks and mitigation measures

Risk	Potential consequence	Mitigation
Fragmented R&D	Duplicated prototypes and incompatible systems	Common architecture, shared facilities, portfolio governance
Proprietary lock-in	No repair, integration, or data autonomy	Interface, data, training, and maintenance clauses in procurement
Premature deep-water ambition	High cost and low reliability	Progressive depth/endurance gates and operational evidence
No first market	Prototypes remain unused	Performance-based service contracts and staged procurement
Weak quality systems	Failures during deployment and loss of user trust	Configuration control, reliability growth, accredited testing
Human-resource shortage	Unsafe operations and slow maintenance	Competency standards, apprenticeships, sea-time requirements
Environmental impacts	Damage to habitats or public opposition	Environmental assessment, acoustic management, monitoring
Cyber and data risk	Loss of control, sensitive data exposure	Secure architecture, access control, update governance, audit logs

CONCLUSION

Underwater technology should be treated as national infrastructure rather than a collection of isolated research projects. It enables ocean science, offshore asset integrity, environmental monitoring, disaster response, submarine-cable resilience, and maritime security. Indonesia's strategic challenge is not the absence of ideas or prototypes, but the lack of an integrated pathway from mission need to certified product, recurring operation, and lifecycle support.

The recommended strategy begins with service-based learning, observation-class systems, mission software, sensor integration, maintenance, and shared testing. It then progresses toward shallow-water AUVs, acoustic networks, persistent observation, higher-value components, and regional services. A national mission ecosystem should connect universities and BRIN, industry, government, regulators, and end users through open interfaces, shared facilities, performance-based procurement, and stage-gate evidence.

By 2045, success should not be defined by complete self-sufficiency. A more realistic and valuable objective is strategic control: Indonesia should own mission architecture, key software, data, integration, maintenance, and selected critical components while participating intelligently in global supply chains. If development is measured through reliability, sea hours, certification, recurring demand, and export capability, Indonesia can move from a buyer of underwater systems to a credible regional innovator in the global ocean economy.

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