ADVANCING MARITIME INNOVATION THROUGH DIGITALISATION, SUSTAINABILITY, AND AUTONOMY: INNO2MARE SCALE UP OF PILOT PROJECTS FROM LAB TO MARKET

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EXTRACT

The maritime sector faces significant challenges in transferring promising research outcomes from pilot implementations to large-scale market deployment. This article presents the EU project's INNO2MARE (Strengthening the capacity for excellence of Slovenian and Croatian innovation ecosystems to support the digital and green transitions of maritime regions) scale-up framework developed to support the transition of innovative maritime technologies from laboratory validation to commercial adoption. The framework combines Technology Readiness Level (TRL) assessment, technical and commercial feasibility analysis, deployment planning, and scalability roadmaps. Three pilot projects are used to demonstrate the approach: a virtual-reality-based maritime fire evacuation training system, an AI-enabled digital twin for sustainable energy management, and AI-supported technologies for autonomous shipping. For each pilot, a dedicated scalability roadmap is developed, defining the transition from prototype development and validation towards operational deployment, replication, and market uptake. The results highlight the importance of structured deployment strategies, realistic TRL assessment, stakeholder engagement, interoperability, regulatory compliance, and sustainable business models. The proposed roadmap-based approach provides practical guidance for reducing the gap between research and market while supporting the digital and green transformation of the maritime sector. The findings contribute to the development of replicable methodologies for scaling maritime innovations and accelerating their adoption across industrial and maritime environments.

1 INTRODUCTION

The maritime sector is changing rapidly. New digital technologies, the need for more sustainable solutions, and the development of autonomous systems are creating new ways of operating ships and managing maritime activities. These trends are reshaping traditional maritime operations, enabling improved efficiency, safety, and environmental performance. However, despite significant advances in research and innovation (R&I), a persistent gap remains between successful pilot developments and large-scale market deployment. Many promising maritime technologies fail to progress beyond the prototype stage, towards Technology Readiness Level (TRL) up to TRL7-9 due to a combination of factors, including conservative industry adoption, regulatory complexity, fragmented stakeholder environments, and varying levels of digital maturity across deployment contexts. Addressing this "pilot-to-market" gap is critical for accelerating the uptake of innovative solutions in maritime ecosystems. The INNO2MARE (Strengthening the capacity for excellence of Slovenian and Croatian innovation ecosystems to support the digital and green transitions of maritime regions) project (2023–2026), funded under the Horizon Europe programme, directly targets this challenge by strengthening innovation capacity in Slovenian and Croatian maritime regions while fostering collaboration with Belgian partners from Antwerp, a reference for highly-innovative maritime ecosystem with high technology implementation rating. The project integrates research, industry, and policy stakeholders to support the green and digital transition of maritime activities, with a particular focus on translating R&I outcomes into deployable, market-ready solutions. This article builds on these insights to examine how digitalisation, sustainability, and autonomy can be effectively advanced through structured scale-up strategies (INNO2MARE scale-up framework) presented by Figure 1.

Fig. 1: INNO2MARE Scale-up framework.

Specifically, it presents the INNO2MARE approach, the transition path from research towards industrial deployment and market uptake to translating pilot projects into market-ready solutions, highlighting methodological innovations, pilot-specific results, and broader lessons for maritime innovation ecosystems. By doing so, it contributes to the development of replicable models for accelerating technology adoption, not only within the maritime sector but also in other complex industrial domains facing similar challenges.

2 METHODOLOGIES

The project developed and applied a TRL-adaptive methodology that aligns feasibility assessment and planning activities with the validated maturity level of each technology covered by all INNO2MARE Pilot projects. The roadmap from lab to market, which is suitable for all three pilot projects is presented in Figure 2 [1]. It consists of 6 main steps with GO-NO GO decision gates (G).

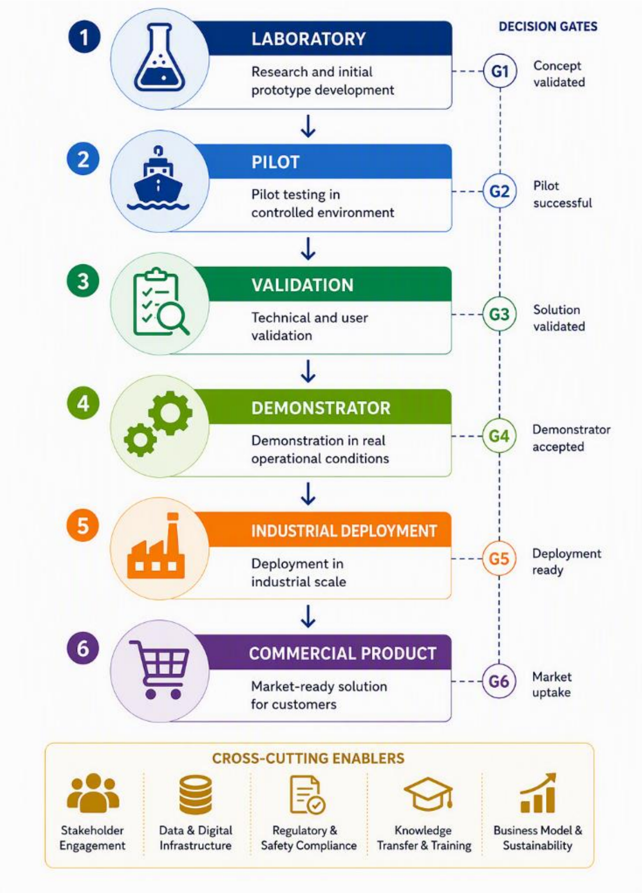

Fig. 2: Generic roadmap from laboratory development to commercial deployment used as the common framework for all three pilot projects.

This approach departs from traditional one-size-fits-all frameworks by tailoring technical and commercial analyses to the specific stage of development of each pilot. It is supported by a suite of four complementary tools:

1) Technology Readiness Level (TRL) assessment tool developed on the basis of official European Union TRL assessment strategy [2]
2) Technical feasibility study framework
3) Commercial feasibility study framework
4) Integrated action plan template

Together, these tools provide a structured and evidence-based approach to guide the transition from prototype to demonstrator and, ultimately, to market uptake.

The application of this methodology across three diverse pilot cases highlights both common and technology-specific challenges in maritime innovation. Cross-cutting findings emphasize the importance of adaptive technology design, robust stakeholder coordination, and realistic Technology Readiness Level (TRL) assessment as key enablers of successful maritime digital innovation. Adaptive technology design is essential to accommodate the heterogeneous digital infrastructures found across ports and pilot sites. Digital solutions should therefore be flexible, scalable, and capable of operating effectively in diverse technical and organizational environments, ensuring successful deployment under varying operational conditions. Robust stakeholder coordination is equally critical in managing the complexity of maritime ecosystems. Effective collaboration among port authorities, technology providers, terminal operators, researchers, public authorities, and other relevant actors requires clear communication, well-defined governance structures, and coordinated planning. These elements facilitate smoother implementation, increase stakeholder acceptance, and support the long-term uptake of digital solutions. Realistic TRL assessment is another fundamental cross-cutting finding. Technology maturity should be evaluated using evidence-based criteria and reviewed regularly throughout the project lifecycle to accurately reflect development progress. Avoiding overestimation of TRLs helps manage stakeholder expectations, reduce implementation risks, allocate resources more effectively, and provide a credible basis for future deployment and commercialization planning. Collectively, these findings demonstrate that successful maritime digital innovation depends not only on technological performance but also on the ability to adapt solutions to diverse digital environments, establish effective collaborative governance across complex stakeholder networks, and maintain transparent and realistic assessments of technology maturity. Emerging regulatory frameworks, particularly those related to artificial intelligence (AI) and sustainability, require that compliance considerations be integrated from the earliest stages of technology development. This includes designing AI systems in accordance with evolving legal and ethical requirements, ensuring alignment with sustainability objectives, and adopting a compliance-by-design approach throughout development, validation, and scale-up.

In the next three chapters all three Pilot projects specifics will be highlighted, which represents the base for development of their Scalability roadmaps.

2.1 Pilot Project 1 - Improved fire evacuation virtual reality (VR) model of a ship engine room applies a TRL-adaptive feasibility and validation methodology, which serves as the core approach for evaluating and scaling the VR fire safety training system. This method ensures that the pilot is assessed according to its actual maturity level (TRL 6–7) using structured tools such as TRL assessment, technical feasibility analysis, and commercial feasibility evaluation, all tailored to deployment readiness rather than early-stage research. It is complemented by a simulation-based experimental methodology, where the system uses CFD-based fire and smoke models within a virtual environment to safely replicate real-life emergency scenarios. Additionally, the pilot incorporates a user-centred validation methodology, involving real users (students, engineers, and seafarers) and structured feedback collection through questionnaires to evaluate usability and training effectiveness. A roadmapdriven action planning methodology supports the transition from pilot to demonstrator through defined phases, milestones, and GO/NO-GO decision criteria, while a risk-based assessment approach systematically identifies technical risks and mitigation strategies to ensure reliable deployment. Together, these elements form a comprehensive, structured methodology that integrates technical validation, user testing, and strategic planning for successful scale-up [3].

2.2 Pilot Project 2 - Digital twin with AI for sustainable and efficient energy management applies a TRL-adaptive, deployment-driven feasibility methodology, centred on real-world validation and iterative system improvement. The core approach combines a TRL-based diagnostic methodology, where the system is assessed at TRL 5 using a structured assessment tool with quality gates. As of July 2026, full deployment at the industrial site at ISKRA is still in progress, and operational validation of this TRL level remains pending. This is complemented by a technical feasibility methodology, which analyses system architecture, data infrastructure, AI models, integration with industrial systems (ERP, SCADA), and deployment requirements in a real industrial environment (ISKRA Kranj). A key distinguishing element is the deployment-validation (learning-by-doing) methodology, where attempted real deployment revealed system limitations and directly informed redesign and improvement, highlighting an iterative, experience-driven approach. The pilot also incorporates a commercial feasibility methodology, evaluating market potential, cost savings, business models, and scalability across industrial and maritime sites. In addition, a data-driven methodology is central, focusing on data collection, cleaning, integration, and AI-based forecasting as the foundation for system functionality. Finally, a structured action-planning (roadmapping) methodology defines phased deployment, validation, and scale-up with clear performance KPIs and GO/NO-GO criteria. Together, these activities provide a structured framework for technology validation, deployment planning, and scalability assessment [4].

2.3 Pilot Project 3 - Autonomous shipping technology supported by AI applies a TRL-adaptive, multi-model validation and deployment methodology, specifically tailored to complex AI-based technologies. The core approach is a TRL-based diagnostic methodology, where different components (trajectory prediction, sea state estimation, and object detection models) are assessed separately using a structured TRL Assessment Tool, ensuring realistic evaluation of maturity based on actual testing environments and operational validation rather than theoretical performance. This is combined with a technical feasibility methodology, which analyses modular system architecture, scalability (cloud and edge computing), hardware/software requirements, and integration with maritime equipment such as sensors and cameras. A key element is the experimental and dual-environment validation methodology, where systems are tested both in controlled settings and in real-world maritime conditions (e.g., offshore vessel testing), supported by a parallel simulation environment to mitigate constraints such as weather and operational limitations. The pilot also employs a data-driven AI methodology, relying on real-world datasets, synthetic data generation, and continuous model training and evaluation to ensure robustness and accuracy. Additionally, a user- and expert-based validation approach is used through structured questionnaires and feedback from maritime domain experts to assess usability and operational relevance. Finally, the methodology includes a risk- and regulation-aware approach, addressing challenges such as sensor reliability, environmental conditions, and compliance with maritime regulations and the EU AI Act, combined with a structured action-planning methodology that defines phased deployment, scalability targets, and GO/NO-GO criteria. Overall, Pilot 3 uses a comprehensive methodology integrating TRL-based assessment, AI model validation, real-world experimentation, and structured scale-up planning [5].

The general view of all three Pilot projects is illustrated in Figures 3a, b and c. The comparison is made by main criterion listed in the first column. Based on INNO2MARE evaluation and TRL assessment report [1] we can predict the current TRL level and the targeted TRL level that can be achieved by the end of INNO2MARE project, 31. December 2026. It is worth to emphasize the different deployment complexity between each Pilot project which varies from low to high, due to different required initial TRL level of the end-user, necessary equipment and IT infrastructure preparation as well as complexity of development of new use cases and their set-up.

CRITERION	PILOT 1 VR-Based Fire Evacuation Training
Technology	Virtual Reality (VR), CFD-based fire and smoke simulation
Initial TRL	6–7
Target TRL	8–9
Main Innovation	Immersive and realistic fire evacuation training in virtual ship engine rooms
Key Features	Realistic scenarios, interactive training, user feedback, safe and repeatable simulations, low-cost deployment
Commercial Application	Maritime education and training institutions
Target Users / Market	Maritime academies, training centres, seafarers, safety training providers
Expected Impact	Improved training effectiveness and safety, reduced training costs
Deployment Complexity	Low (standalone application, standard hardware)
Business Model	One-time purchase (+ optional hardware, custom scenarios as service)

a) Characteristics of Pilot project 1.

CRITERION	PILOT 2 AI-Powered Digital Twin for Energy Management
Technology	Digital Twin, IoT, Data Analytics, AI Forecasting
Initial TRL	5
Target TRL	7–8
Main Innovation	AI-powered digital twin for real-time energy optimization and predictive maintenance
Key Features	Real-time data integration, AI forecasting, energy savings, dashboards, what-if analysis
Commercial Application	Industrial plants, shipyards, ports, manufacturing facilities
Target Users / Market	Energy managers, facility managers, plant operators
Expected Impact	Energy cost reduction, improved efficiency, lower emissions
Deployment Complexity	Medium (integration with industrial systems and data sources)
Business Model	Hybrid: deployment + subscription (SaaS)

b) Characteristics of Pilot project 2.

CRITERION	PILOT 3 AI Modules for Autonomous Navigation
Technology	AI (Machine Learning, Deep Learning), Sensor Fusion, Edge/Cloud Computing
Initial TRL	4–5
Target TRL	7–8
Main Innovation	AI models for sea state estimation, object detection and trajectory prediction
Key Features	Multi-model AI, high accuracy, scalable architecture, real-time decision support
Commercial Application	Ships, offshore vessels, personal watercraft
Target Users / Market	Ship operators, fleet owners, rental companies, port authorities
Expected Impact	Enhanced navigation safety, reduced fuel consumption, situational awareness
Deployment Complexity	High (sensors, real-time data, environmental factors)
Business Model	Hybrid: hardware + software or subscription-based service

c) Characteristics of Pilot project 3.

Fig. 3: Comparison of three Pilot projects.

3 PILOT PROJECTS JOURNEY FROM LAB TO MARKET

3.1 Pilot Project 1: Improved fire evacuation VR model of a ship engine room

The scalability of Pilot Project 1 is planned as a structured, TRL-guided transition from a validated laboratory VR prototype to a commercially deployable maritime training solution (Figure 4). The pilot aims to improve maritime firefighting training by combining a virtual reality engine room environment with realistic fire-spread simulations derived from Computational Fluid Dynamics (CFD), thereby creating a safer and more immersive training experience for maritime personnel.

Fig. 4: VR fire evacuation training - Scalability roadmap.

For successful implementation, organizations must provide a suitable hardware and software environment. The required hardware consists primarily of a PC workstation, VR headset/glasses, and supporting VR equipment capable of running immersive training simulations. The INNO2MARE project demonstrates a portable deployment concept, where the complete VR training system can operate as a mobile unit and be transported between training locations.

The software requirements include a virtual reality training platform, a detailed 3D model of a ship engine room, CFD-based fire-spread simulation models, visualization software, and user-interaction modules that enable trainees to navigate emergency scenarios and practice firefighting procedures in a realistic virtual environment. The solution combines advanced fire modelling with immersive VR technologies to deliver realistic maritime safety training.

The implementation process (Figure 4) begins with infrastructure preparation and installation, where organizations establish the required VR hardware environment, configure software components, and verify system performance. This is followed by deployment of the VR engine room model and integration of CFD-based fire scenarios. Proper installation procedures, technical documentation, and user guides are essential to ensure that the solution can be consistently deployed at different locations without direct involvement from the original developer [1].

The next stage focuses on user validation and training assessment. The system is initially evaluated in controlled environments such as laboratories, universities, and maritime training facilities. Validation includes technical performance testing, system stability assessments, and structured user evaluations involving maritime professionals, marine engineers, firefighters, students, and trainees. The objective is to confirm realism, usability, learning effectiveness, and operational reliability before broader deployment. Once laboratory validation is completed, the project moves into the demonstrator phase, where the VR training platform is deployed in real maritime education and training environments. Maritime academies, training centres, and professional training providers become the primary deployment sites. At this stage, scalability depends on the ability to reproduce installations efficiently, maintain stable performance outside the development environment, and support independent operation by instructors and trainees. A critical element of scalability is replication and independent deployment. Training centres must be able to install, configure, and operate the solution without continuous developer support. This requires standardized hardware configurations, documented installation procedures, stable software releases, and repeatable deployment workflows. Successful replication across multiple institutions demonstrates that the system can move beyond pilot testing and become a transferable training product.

At the market level, scalability is supported by the relatively low deployment complexity of the solution. The system is designed as a standalone VR application that can operate on standard VR hardware and workstation computers without requiring extensive site-specific infrastructure. This modular deployment model allows maritime academies, vocational training providers, and shipping companies to adopt the solution incrementally and extend it with additional training scenarios as needed.

In summary, the scalability of Pilot Project 1 is planned as an iterative and validation-driven process in which successful expansion depends on the availability of standard VR hardware, specialized VR and CFD simulation software, validated training effectiveness, repeatable installation procedures, and the ability to independently deploy the solution across maritime academies and training centres. The transition from pilot to market is guided by measurable performance, usability, realism, and deployment-readiness criteria, ensuring that the solution remains robust, transferable, and commercially viable [1], [6].

3.2 Pilot Project 2: Digital twin with AI for sustainable and efficient energy management

Pilot Project 2 addresses the development and deployment of a digital twin platform enhanced with AI services for sustainable and efficient energy management in industrial and maritime environments. The scalability strategy follows a structured roadmap that guides the transition from a laboratory prototype to a commercially deployable solution through progressive validation, operational deployment, and market expansion (Figure 5).

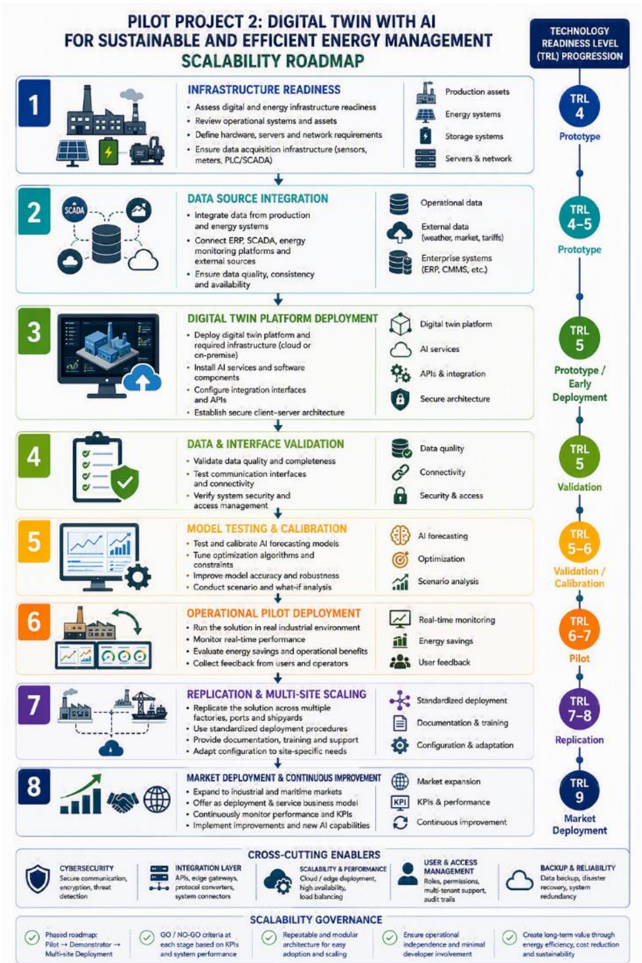

Fig. 5: Digital Twin - Scalability roadmap.

The first stage focuses on infrastructure readiness, which represents the foundation for successful deployment. Before implementation, organizations must assess the maturity of their digital and energy infrastructure, including production assets, energy generation and storage systems, communication networks, and data acquisition capabilities. Particular attention is devoted to evaluating the availability of sensors, energy meters, programmable logic controllers (PLCs), and supervisory control and data acquisition (SCADA) systems, as these components provide the operational data required by the digital twin.

The second stage addresses data source integration, where information from production processes, energy management systems, enterprise software, and external sources is consolidated into a unified data environment. Data quality, consistency, and accessibility are critical factors because the accuracy of digital twin simulations and AI-based forecasting depends directly on the reliability of incoming data streams. Integration interfaces must therefore support interoperability with existing ERP, SCADA, CMMS, and cloud-based platforms.

Following successful integration, the project proceeds with digital twin platform deployment. This stage involves establishing the digital twin infrastructure, configuring client–server architecture, implementing AI services, and deploying application programming interfaces (APIs) required for communication between operational systems and analytical modules. The deployment architecture developed within the project supports both cloud-based and on-premise implementations, enabling adaptation to different industrial requirements while maintaining cybersecurity and operational reliability.

The fourth stage consists of data and interface validation, where communication links, data completeness, system security, and access management mechanisms are thoroughly verified. This phase ensures that all connected systems operate reliably and that the digital twin can accurately represent the physical environment in near real time. Successful completion of this stage corresponds to achieving a validated operational framework suitable for industrial testing.

The next phase focuses on model testing and calibration. AI forecasting algorithms, optimization routines, and simulation models are evaluated using operational data collected from the deployment environment. Calibration activities aim to improve prediction accuracy, optimize energy management decisions, and validate scenario-analysis capabilities. The outcome of this stage is a robust and reliable analytical framework capable of supporting industrial decision-making processes.

Once the platform and models have been validated, the solution enters the operational pilot deployment stage. Within the INNO2MARE project, deployment activities at ISKRA Kranj, Slovenia, demonstrated the importance of operating the system under real industrial conditions. During this phase, the solution is assessed through continuous monitoring of technical performance, energy savings, optimization effectiveness, and user acceptance. The pilot serves as the primary mechanism for evaluating real-world applicability and operational benefits.

After successful pilot validation, scalability is achieved through replication and multi-site deployment. The modular architecture of the digital twin enables implementation across different industrial facilities, ports, shipyards, and other energy-intensive environments without requiring significant modifications to the core platform. Standardized deployment procedures, configurable interfaces, comprehensive documentation, and user training support efficient transferability between deployment sites.

The final stage addresses market deployment and continuous improvement. At this level, the solution evolves from a project-specific implementation into a repeatable deployment and service model. Expansion is supported through continuous monitoring of key performance indicators (KPIs), including forecasting accuracy, operational reliability, energy efficiency improvements, and cost reduction. The platform architecture enables the integration of additional AI functionalities and supports long-term adaptation to emerging operational and sustainability requirements.

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Throughout all roadmap stages, scalability is supported by several cross-cutting enablers. These include cybersecurity mechanisms, integration-layer components, scalable cloud and edge-computing infrastructure, user and access management, as well as backup and reliability services. Furthermore, progression between stages is governed by clearly defined GO/NO-GO decision criteria based on technical performance, operational readiness, and achievement of predefined KPIs.

In summary, Pilot Project 2 follows a structured scalability pathway that extends beyond technology development and encompasses infrastructure readiness, data integration, deployment validation, operational testing, and market-oriented replication. The roadmap provides a practical framework for transforming a laboratory-scale digital twin prototype into a robust and commercially viable energy management solution capable of deployment across industrial and maritime sectors.

3.3 Pilot Project 3: Autonomous shipping technology supported by AI

The scalability of Pilot Project 3 (Autonomous Shipping Technology Supported by AI) is planned as a progressive, validation-driven pathway that moves from controlled testing environments toward operational deployment across maritime fleets. The solution is based on advanced AI, machine learning, computer vision, and autonomous navigation technologies designed to improve maritime safety through trajectory prediction, anomaly detection, sea-state estimation, and object recognition [1]. Unlike conventional software solutions, the scalability of autonomous maritime technologies depends on the successful integration of digital intelligence with real-world vessel operations, regulatory requirements, and heterogeneous maritime environments.

Figure 6 presents the scalability roadmap for Pilot Project 3. The roadmap illustrates the transition from infrastructure and data readiness through AI model development and laboratory validation toward demonstrator deployment, operational pilot implementation, fleet replication, and commercial market deployment. Progression between stages is governed by predefined performance indicators, including prediction accuracy, anomaly detection reliability, operational robustness, user acceptance, system availability, and compliance with maritime regulatory requirements.

Fig. 6. Autonomous Shipping Technology Supported by AI - Scalability roadmap.

The first stage focuses on infrastructure and data readiness. Successful implementation requires organizations to establish the necessary hardware and communication infrastructure, including AI-capable workstations, high-performance computing (HPC) resources, onboard sensors, vessel monitoring systems, navigation equipment, cameras for visual perception applications, and communication networks capable of transmitting real-time operational data. This stage also involves assessing the availability of existing vessel systems and determining infrastructure requirements for subsequent deployment activities.

The second stage addresses data acquisition and preparation, which provides the foundation for all AI-driven functionalities. Organizations must establish reliable access to vessel positioning data, navigation parameters, operational sensor outputs, environmental observations, and visual information collected through onboard monitoring systems. Historical maritime datasets, synthetic datasets, and real-world operational data are collected, cleaned, validated, and prepared for model development. The quality and availability of these datasets directly influence the performance of trajectory prediction [7], sea-state estimation, object recognition, and anomaly detection algorithms [5].

Following data preparation, the project proceeds with AI model development. This stage focuses on the implementation and training of machine learning, deep learning, Bayesian modelling, and computer vision algorithms. The project utilizes trajectory forecasting models, anomaly detection methods, sea-state estimation approaches, and AI-based perception systems designed to support autonomous navigation and maritime decision-making. The objective is to create robust and technically mature AI components capable of operating under diverse maritime conditions.

The fourth stage consists of laboratory validation, during which AI algorithms are evaluated using historical and simulated datasets. Validation activities focus on assessing prediction accuracy, anomaly detection performance, computational efficiency, robustness, and overall reliability. At this stage, scalability remains limited to controlled experimental environments, with the primary objective of demonstrating the technical feasibility and performance of the developed AI components before deployment in operational settings.

A critical step in the scalability process is system integration and demonstrator deployment. During this phase, individual AI modules are integrated with vessel navigation systems, sensor networks, monitoring platforms, and operational workflows. The system must be capable of processing live vessel data streams and providing accurate forecasts, anomaly alerts, sea-state assessments, and navigational support in near real time. Successful completion of this phase demonstrates interoperability with existing maritime systems and establishes the technological foundation for operational deployment.

The next phase involves operational pilot deployment under real maritime conditions. The integrated solution is deployed on pilot vessels, where it operates continuously and supports real-world navigation and decision-making processes. Performance is evaluated through operational monitoring, user feedback, situational awareness improvements, and safety-related indicators. The objective of this stage is to verify that the solution can function reliably in operational environments without continuous developer involvement while providing measurable benefits to maritime stakeholders.

After successful pilot validation, scalability is enabled through fleet replication and multi-vessel deployment. The solution adopts a modular architecture in which each vessel can operate as an independent deployment unit while remaining connected to centralized cloud-based monitoring and analytics services. Containerization technologies such as Docker and orchestration platforms such as Kubernetes facilitate standardized deployment, maintenance, and scaling across multiple vessels and operational locations. This approach enables efficient adaptation to different vessel types without requiring significant modifications to the underlying AI framework.

The final stage focuses on commercial deployment and continuous improvement. At this level, the solution evolves from individual pilot implementations into a repeatable and

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commercially viable offering. The technology can be delivered either as onboard hardware-and-software installations or as subscription-based digital services. Market expansion is expected to proceed gradually, beginning with pilot vessels and demonstration fleets before extending to larger commercial operators. Continuous monitoring of key performance indicators (KPIs), combined with ongoing refinement of AI models and system functionalities, supports long-term operational improvement and wider market adoption.

Throughout all stages of the roadmap, scalability is supported by several cross-cutting enablers, including cybersecurity and secure communication mechanisms, maritime regulatory compliance, data governance and quality management, cloud and edge computing infrastructure, fleet monitoring and analytics services, and user training for operational adoption. Furthermore, progression between roadmap stages is governed by GO/NO-GO decision criteria based on predefined KPIs and operational performance objectives.

In summary, the scalability of Pilot Project 3 follows a structured eight-stage implementation roadmap that extends from infrastructure preparation and AI model development to fleet-wide replication and commercial deployment. Scalability is achieved not through simple software replication, but through systematic validation, integration, operational testing, and progressive expansion across increasingly complex maritime environments. This approach provides a practical pathway for transforming autonomous shipping technologies from laboratory-scale prototypes into deployable and commercially sustainable maritime solutions.

3.4 Critical Factors for Successful Scalability from Lab to Market

Many maritime technologies fail to move from successful pilots to market deployment due to conservative adoption practices, regulatory complexity, fragmented stakeholder environments, and varying levels of digital maturity. The experiences gained across the three INNO2MARE pilot projects enabled the identification of the key factors that influence successful scalability from laboratory validation to sustainable market deployment.

Fig. 7. Key factors for successful scaling of maritime innovations from pilot deployment to sustainable market impact.

Figure 7 summarizes the key factors that enable successful scaling of maritime innovations. These include a clear value proposition, active stakeholder engagement, technology maturity and reliability, data quality and availability, system integration and interoperability, organizational capabilities, sustainable funding, regulatory compliance, strong partnerships, and long-term scalability. Together, these factors create the foundation for transforming pilot solutions into market-ready applications.

The scalability of maritime innovations depends on more than technological performance alone. Successful scale-up requires validated technology readiness, operational testing in real environments, integration with existing systems, commercial viability, regulatory alignment, and active cooperation among stakeholders. The findings from all three pilot projects demonstrate that scalability is achieved through a combination of technological, organizational, and business-related factors rather than through technology development alone.

4 CONCLUSIONS

Successfully scaling maritime innovations from the laboratory to the market requires a holistic approach that extends beyond technological development and the achievement of higher Technology Readiness Levels (TRLs). As demonstrated by the three pilot projects presented in this study, successful commercialization depends on the combination of technical maturity, operational validation, stakeholder engagement, regulatory compliance, and sustainable business models.

The experiences gained within the INNO2MARE project show that successful scale-up requires continuous validation in real operational environments, effective knowledge transfer, close cooperation between technology developers and end users, and seamless integration with existing industrial and maritime systems. Across all pilot projects, scalability was achieved through structured deployment roadmaps supported by clearly defined performance indicators and GO/NO-GO decision criteria.

The main contribution of this work is the development and application of a common scale-up framework that supports the transition from laboratory validation to sustainable market impact. The scalability roadmaps and critical success factors identified within the INNO2MARE project provide practical guidance for researchers, technology developers, and industrial stakeholders seeking to accelerate the adoption of maritime innovations. By combining technological maturity, business readiness, ecosystem collaboration, and regulatory alignment, innovative solutions can contribute more effectively to safer, smarter, and more sustainable maritime operations.

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