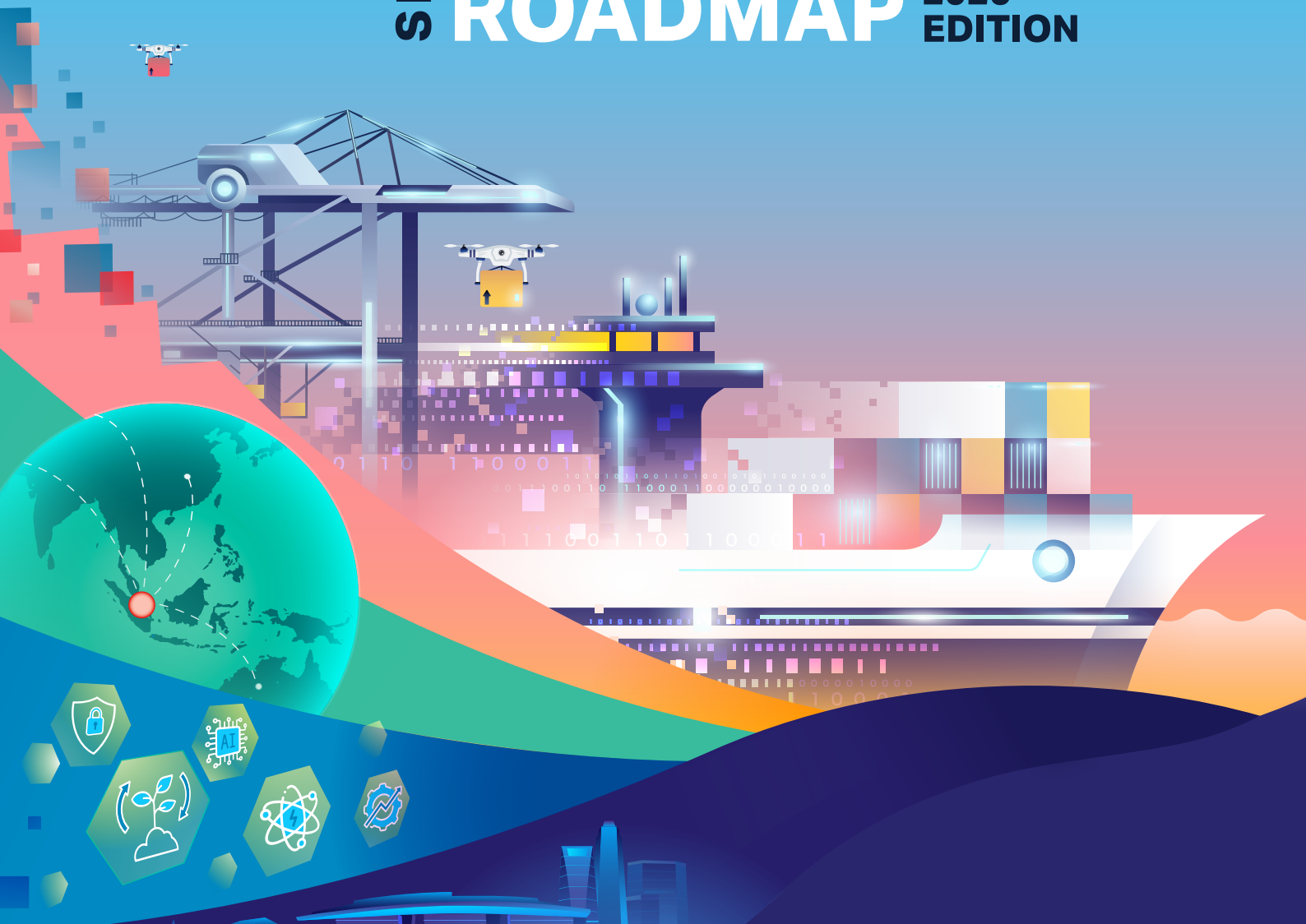


SINGAPORE MARITIME TECHNOLOGY & RESEARCH ROADMAP 2026 EDITION



**Set Sail into the Next Wave
of Maritime Innovation**



Cover Rationale

Anchored by the theme “Set Sail into the Next Wave of Maritime Innovation”, the cover visual embodies Singapore’s integrated maritime vision. A sleek cargo vessel advances toward a radiant horizon, symbolising momentum and transformation. On the left, the globe motif, with Singapore at its centre, signifies the nation’s pivotal role as a connected global maritime hub. The constellation of icons highlight automation, sustainability, and digital innovation, representing the four thrusts of Autonomous Port Operation, Safe and Efficient Delivery of Alternative Energy, Smart Ships, and Intelligent and Integrated Port Services. The waveforms dissolving into pixels evoke the digitalisation of maritime operations, while the futuristic city skyline grounds the vision in Singapore’s dynamic urban landscape. Together, these elements visually reinforce the roadmap’s goals: to identify opportunity areas, guide research and development initiatives, and position Maritime Singapore at the forefront of global innovation over the next five to ten years.

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Foreword

Professor LOW TECK SENG

*Chairman of the Board and Governing Council
Singapore Maritime Institute (SMI)*

Maritime has always been at the heart of Singapore's story. From a historic trading port to today's global hub port and international maritime centre, the maritime sector is our economic lifeline – connecting us to the world, creating quality jobs, and underpinning our competitiveness.

The COVID-19 pandemic exposed vulnerabilities but also accelerated digital transformation, demonstrating that resilience is built on agility and intelligence. As we advance our ambitions in autonomy, digitalisation, and security, decarbonisation remains the defining imperative, serving not as a constraint, but as a guiding lens to ensure every innovation contributes to a net-zero maritime future.

In alignment with the International Maritime Organization's 2050 greenhouse gas emissions target, Singapore is pioneering safety standards and operational protocols for the future of fuel – from methanol and ammonia to electrification – through real-world trials and global partnerships. Beyond decarbonisation, we are also accelerating the adoption of smart port technologies, autonomous systems, and data-driven operations across the maritime ecosystem.

The national Research, Innovation and Enterprise 2030 plan, backed by a S\$37 billion investment over the next five years, provides the foundation for this transformation. It sharpens our focus on translating research into real-world impact, building deep technology talent, and leveraging advanced capabilities in artificial intelligence and engineering.

Building on this foundation, this refreshed Maritime Technology & Research Roadmap sets out our ambitious course for the coming decade across four strategic thrusts: Autonomous Port Operation, Safe and Efficient Delivery of Alternative Energy, Smart Ships, and Intelligent and Integrated Port Services.

Our vision is clear: to build a future-ready, sustainable, and globally competitive maritime sector that continues to serve Singapore's strategic interests and economic prosperity. I invite our industry leaders, researchers, innovators, and partners to join us in bringing this Roadmap to life by translating innovation into real-world deployment.

With collective effort, strategic focus, and bold execution, I am confident that Singapore will continue to stay ahead of the curve and remain a vital maritime hub for generations to come.



Mr ANG WEE KEONG

Chief Executive

Maritime and Port Authority of Singapore (MPA)

Singapore has grown from humble beginnings to become one of the world's leading maritime hubs, thanks to the foresight and enterprising spirit of our pioneers. Today, we are an open, reliable, and trusted maritime hub that underpins global trade and serves as a key engine of Singapore's economy. We are home to more than 200 international shipping groups and one of the world's busiest ports, handling around 140,000 vessel calls annually with connections to over 600 ports.

Research and innovation have been key to the growth and resilience of Maritime Singapore. The previous edition of the Maritime Technology & Research Roadmap outlined strategic priorities to transform the sector into one that is advanced, efficient, and safe, by embracing smarter technologies and advancing sustainability. These efforts paved the way for the establishment of maritime Centres of Excellence and the implementation of the Maritime Transformation Programme.

Over the years, MPA and SMI have worked closely with our research and industry partners to strengthen maritime research and development capabilities and prepare our workforce for the future.

As the industry faces structural shifts driven by energy transition, rapid technology development, and supply chain reconfiguration, it is timely to refresh the roadmap. The 2026 edition builds on earlier foundations to guide the next phase of research and development efforts, strengthening Singapore's competitiveness and resilience as a leading global maritime innovation and technology hub.

Collaboration is essential to achieving this vision. We invite local and international partners from research and technology communities, industry, and government agencies to join us in translating research into practical solutions. Together, we can shape a strong, resilient, and future-ready Maritime Singapore.

2

Executive Summary



The Singapore Maritime Technology & Research Roadmap 2026 edition articulates a bold vision to secure Singapore as a global leader in maritime innovation. It provides a comprehensive strategy to fortify resilience, drive productivity, and catalyse innovation across Singapore's maritime ecosystem. The Roadmap addresses key challenges, including manpower shortages, land and sea space limitations, and increasingly stringent global decarbonisation targets.

To achieve this, the Roadmap focuses on four Technology & Research thrusts to transform vessel and port operations:

- 1. Autonomous Port Operation** – embeds intelligence and automation into port operation
- 2. Safe and Efficient Delivery of Alternative Energy** – supports a multi-fuel ecosystem with safe handling and fast delivery
- 3. Smart Ships** – transforms vessel from a standalone asset into a highly connected, intelligent node
- 4. Intelligent and Integrated Port Services** – provides a seamless and coordinated port call experience

These advancements are underpinned by key enablers such as policy and feasibility studies, artificial intelligence (AI) and machine learning, maritime Internet of Things (IoT) and digital connectivity, additive manufacturing, robotics, cybersecurity and trust technologies, as well as quantum technologies – all of which are set to reshape and redefine maritime operations. Singapore is committed to translating research outputs into tangible, operational capabilities. Through coordinated efforts by the Maritime and Port Authority of Singapore (MPA), Singapore Maritime Institute (SMI), industry partners, and research institutions (RIs), Singapore has cultivated a robust innovation ecosystem. This ecosystem, supported by funding initiatives and international collaboration networks, is designed to catalyse knowledge exchange, de-risk new technologies, and nurture the talent pipeline required for sustained maritime transformation.

By aligning efforts and deepening partnerships, Singapore will strengthen its role as a trusted, resilient, and future-ready global maritime hub, where research, technology, and industry converge to redefine maritime operations for the decades ahead.

The Next Wave

of Singapore's Maritime Future

Technology & Research Thrusts

Autonomous Port Operation

Future-ready port operating with no man on the ground

Safe and Efficient Delivery of Alternative Energy

Net-zero emissions from the maritime sector

Smart Ships

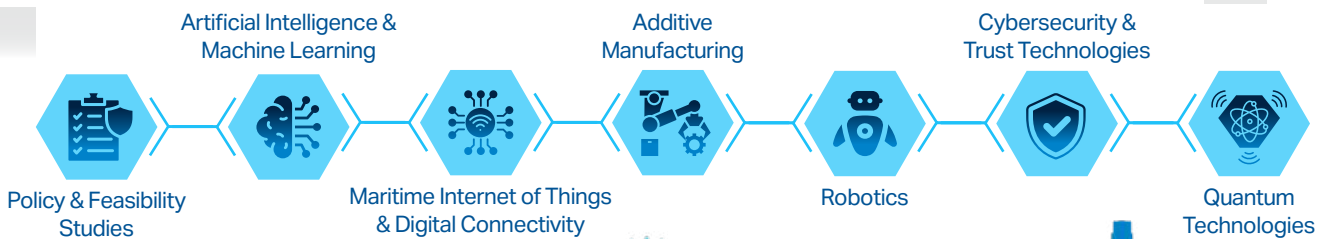
Safe remote and autonomous operations of ships

Intelligent and Integrated Port Services

Singapore as an efficient and trusted one-stop port for ships



Enablers



Policy & Feasibility Studies

Maritime Internet of Things & Digital Connectivity

Robotics

Quantum Technologies



3

| Motivations



3.1 Securing Singapore's Position as the Global Maritime Hub

Today, the maritime sector is a cornerstone of Singapore's economy, contributing over 6% of Singapore's gross domestic product and supporting approximately 140,000 jobs.¹ This critical role is further underscored by Singapore retaining its position as the world's leading maritime centre for the 12th consecutive year in the 2025 Xinhua-Baltic International Shipping Centre Development Index.² This reflects not only Singapore's strategic location and global connectivity, but also its robust maritime ecosystem and infrastructure that is underpinned by a strong government commitment to innovation.





Singapore is
home to



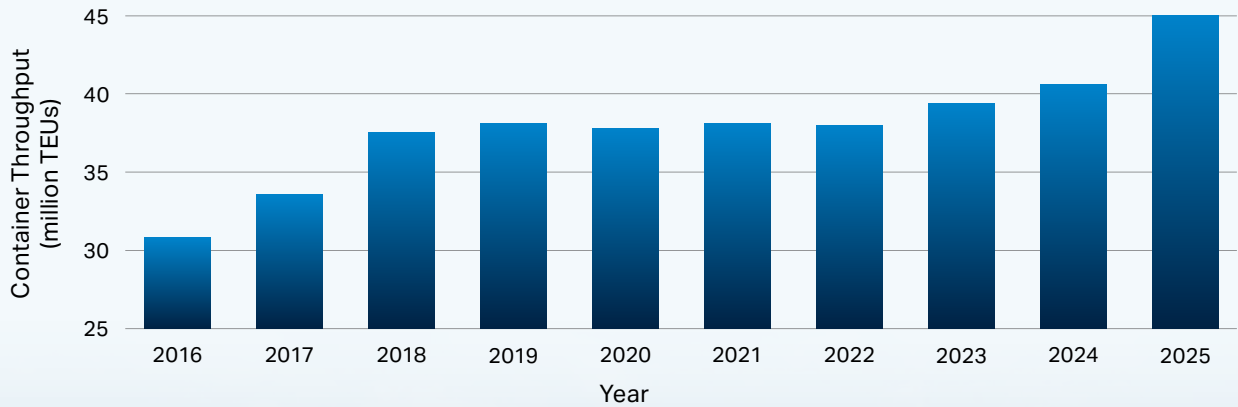
over 200
international shipping groups.

Singapore is home to over 200 international shipping groups, with more than 35 maritime companies establishing or expanding their operations in Singapore in 2025.³ This diverse concentration of expertise creates a vibrant ecosystem for comprehensive maritime services, business growth, and cross-disciplinary collaboration in research and development (R&D), and innovation.



Beyond its role as the world’s largest container transshipment hub, Singapore has cultivated a reputation for reliability, safety, and efficiency. In 2025, the port of Singapore handled a record high of 44.66 million Twenty-Foot Equivalent Units (TEUs),⁴ linking over 600 ports worldwide and serving as a powerful testament to its operational excellence and capability.⁵ As global trade demands faster and more coordinated cargo flows, strengthening intermodal connectivity across transport modes has become increasingly important.

Annual Container Throughput 2016 – 2025



(Source: data.gov.sg)

Being the world’s top bunkering port, Singapore supplied 56.77 million tonnes of marine fuel in 2025. Notably, this volume includes 1.95 million tonnes of alternative fuels, signalling a shift toward sustainability.³ This commitment is further demonstrated by the successful completion of the world’s first ship-to-container ship methanol bunkering trial,⁶ the ammonia fuel trial onboard a Singapore-flagged ammonia-powered vessel, and the publication of a technical reference for methanol bunkering.⁷ These efforts pave the way for the sector’s energy transition.



Maersk and Hong Lam Marine Pte Ltd successfully conducted the world’s first ship-to-containership methanol bunkering operation of a Maersk’s container vessel in Singapore on 27 July 2023.

3.2 Turning Challenges into Strategic Advantages

To sustain its leadership position, Singapore's maritime industry must strategically strengthen its productivity and resilience across four key dimensions: manpower, land, sea space, and carbon emissions. These dimensions present opportunities to catalyse innovation; through targeted R&D and complemented by regulatory agility and international partnerships, Singapore can advance human-centred automation, optimise the use of physical space, and develop scalable green solutions.



Manpower

Across the maritime industry, a persistent shortage of skilled workers, from certified seafarers and engineering officers to port technicians and control-room operators, has placed growing pressure on fleet and terminal operations.⁸ In Singapore, the pressure is mounting due to an ageing population,⁹ while adjacent sectors compete for the same digital and technical talent.

Central to this challenge is the evolution of the skills required across the sector. Daily operations are becoming more data-driven, digital, and AI-enabled.¹⁰ In parallel, alternative fuels introduce new safety, engineering, and compliance competencies.¹¹ Studies project that by the mid-2030s, a significant number of seafarers will require additional training to safely operate vessels powered by alternative fuels and systems, highlighting the substantial scale of re-skilling needed for the industry.¹²

This rapidly evolving manpower landscape is a priority for Maritime Singapore, driving efforts on human-centred automation and advanced decision-support systems. Advanced training technologies and job redesign toolkits will accelerate competencies and skills in alternative fuel handling and data-rich operations, while making new roles more engaging, learnable, and resilient.¹¹ These initiatives aim to equip the maritime workforce with the skills to adapt to rapid technological and regulatory changes, while reinforcing Singapore's position as a trusted and efficient maritime hub.



Land

Maritime cargo volumes are expected to continue growing steadily, with the United Nations Conference on Trade and Development (UNCTAD) projecting seaborne trade to grow at an annual average of 2% from 2026 to 2030.¹³ As a small island city-state, Singapore's unique circumstances require comprehensive, long-term planning for various use cases, such as maritime, housing, industrial, and commercial needs. These spatial constraints require each parcel of land to be used efficiently and productively. This vision has guided the long-term planning to consolidate all container operations at Tuas, and has also paved the way for a revitalised southern waterfront and future urban development.¹⁴

The Tuas Port reflects Singapore's strategic long-term planning approach in shaping the future of maritime logistics. By consolidating all container operations into a single, state-of-the-art fully automated terminal, Tuas Port leverages integrated planning systems, advanced automation, and data-driven orchestration to maximise container throughput per hectare.

Upon its projected completion in the 2040s, Tuas Port will have a handling capacity of



65 million TEUs annually.¹⁵

As global trade demands faster and more coordinated cargo flows, strengthening connectivity across transport modes will become increasingly important. Beyond optimising operations within Tuas Port, Singapore will establish seamless linkages from the terminal to road and maritime networks, inland depots, and air cargo hubs.¹⁶ High-capacity road corridors, smart gate systems, and digitally coordinated trucking help to smooth the movement of containers in and out of the port, while potential maritime links can further improve resilience.¹⁷

■ When fully completed in the 2040s, Tuas Port will be the world's largest fully automated port, capable of handling 65 million TEUs per annum. (Artist impression. Image credit: PSA Singapore)





Sea Space

The strategic use of sea space is fundamental to ensure Maritime Singapore remains competitive and resilient in the face of increasing vessel traffic, technological transformation, and evolving operational requirements.

Optimising sea space is increasingly challenging as Singapore faces growing congestion within its limited waters. Global shipping disruptions, such as the re-routing of vessels around the Red Sea in 2024, intensified pressures on major transshipment hubs. Carriers had to discharge larger cargo volumes in Singapore to recover schedules.¹⁸ Consequently, in May 2024, MPA reported that while most container vessels were able to berth on arrival, average waiting times were about two to three days when rescheduling of arrival schedules was not feasible.¹⁹

As global trade volumes grow, vessel traffic is expected to intensify, placing greater strain on navigational routes, anchorages, and port waters. Compounding this challenge is the evolving profile of vessels calling at Singapore during this period of transition, with a mix of ageing vessels and alternative-fuelled ships entering service. These vessels often have differing operational characteristics, safety requirements, and handling needs, adding



layers of complexity to traffic management and port operations. As a result, Singapore would need to balance safety, efficiency, and sustainability while optimising the use of the constrained sea space.

While most of Singapore's port waters is dedicated to maritime activities, selected zones are allocated for biodiversity conservation, aquaculture, utilities, and recreational activities. Balancing these diverse and sometimes competing needs require careful, integrated planning.

Looking ahead, large-scale coastal protection and reclamation initiatives will introduce additional complexity to sea space management. This evolving landscape underscores the importance of R&D and technology in ensuring that maritime operations remain safe, efficient, and well-coordinated as Singapore's coastline evolves.²⁰





Carbon Emissions Targets

Global warming and climate change present risks to the maritime industry. Their impacts include rising sea levels and more frequent extreme weather events, which can threaten port infrastructure and disrupt shipping operations, respectively. Today, international shipping contributes over 80% of global trade volumes, and approximately 3%²¹ of global greenhouse gas (GHG) emissions. Decarbonisation of the shipping sector is therefore important for the global climate effort. The International Maritime Organization (IMO) has set ambitious global targets for the shipping sector, with the goal of achieving net-zero GHG emissions from international shipping by, or around 2050. To guide this transition, the IMO has also introduced interim checkpoints. By 2030, international shipping is expected to reduce emissions by at least 20% compared to 2008 levels. By 2040, the target rises to at least 70%.²²

■ *Hydromover by Yinson GreenTech – Singapore's first fully electric cargo vessel, featuring swappable batteries, zero emissions, and lower operating costs.*





- *Launch and inauguration of President 100 by Pinnacle Marine (Singapore) Pte Ltd – Singapore's first harbour craft fully powered by B100 biodiesel, marking a significant milestone in advancing sustainable maritime operations. The Maritime Energy & Sustainable Development Centre of Excellence (MESD) at Nanyang Technological University collaborated with Pinnacle Marine on a 1,000-hour real-time sea trial with President 100.*

The 83rd session of IMO's Marine Environment Protection Committee (MEPC 83) advanced several measures to strengthen maritime decarbonisation and environmental protection, and approved mid-term GHG reduction measures under MARPOL Annex VI. Although IMO members voted to postpone the voting of measures for a year, Singapore remains committed to maritime decarbonisation and steadfast in our commitment to work with the IMO and fellow Member States to secure the future of maritime. The adjournment provides more time for Member States to build a broader consensus on areas such as sustainable fuel certification. MEPC 83 also approved regulations to enhance fuel oil data transparency amendments to the NO_x Technical Code 2008. The Committee further updated guidelines on the Inventory of Hazardous Materials, agreed to an experience-building phase for the Hong Kong Convention on ship recycling, and initiated work on a new biofouling control framework.²³

MPA, in line with its national target of achieving net-zero by 2050, is developing capabilities to support multiple pathways in the Port of Singapore. For instance, MPA targets for Singapore's domestic harbour craft sector to achieve net-zero emissions by 2050, and requires all new harbour crafts operating in local waters to either be fully electric, capable of using B100 biofuel (100% biodiesel), or compatible with net-zero fuels such as hydrogen. As a major bunkering hub, Singapore is also building up robust alternative fuel value-chains to offer a range of fuel solutions for the sector.

Both port terminal operators, PSA Corporation and Jurong Port, have committed to ambitious decarbonisation goals, aiming to reduce total port emissions by at least 60% by 2030, as compared to 2005 levels, and to achieve net-zero emissions by 2050.²⁴ By 2050, Tuas Port container handling operations will be powered by electricity, supplemented by low and near-zero energy sources.²⁵

3.3 Building Partnerships in Maritime Innovation

Singapore's position as a global hub port and international maritime centre is underpinned by three core strengths:



Strategic geographic location



World-class port infrastructure



Vibrant maritime ecosystem

As other major maritime nations continue to advance in maritime technologies, there are opportunities for Singapore to collaborate with complementary partners and strengthen our advantages. Singapore must remain agile and committed to advancing innovation, digitalisation, and sustainability to meet evolving industry demands.²⁶

Singapore's partnerships with countries and overseas ports under the Green and Digital Shipping Corridor initiative reflect a commitment to advancing decarbonisation and digitalisation across key global trade routes. Working with partners in countries such as Australia, China, India, Japan, Republic of Korea, the Netherlands, and the United States, Singapore is co-developing designated corridors to facilitate the adoption of zero and near-zero GHG emission technologies and fuels, strengthen end-to-end digital connectivity, and enhance operational efficiency. These collaborations focus on aligning infrastructure readiness, harmonising data and digital standards, and conducting joint trials of green and digital solutions across international borders.

Through such partnerships, Singapore is facilitating the transition towards cleaner and more resilient maritime supply chains while reinforcing its role as a leading global maritime hub.²⁷

■ *Jurong Port – Singapore's premier gateway for multipurpose cargo. (Photo credit: Jurong Port)*



3.4 Accelerating the Maritime and Technology Convergence

In recent years, the maritime industry has undergone marked transformation driven by global disruptions, technological developments, and sustainability efforts. The COVID-19 pandemic revealed vulnerabilities in crew change, port access, and supply chain reliability. In response, the industry accelerated its shift towards automation, exploring innovations such as the Maritime Autonomous Surface Ships (MASS) to reduce manpower dependency, while strengthening operational resilience.²⁸

In Singapore, the transformation of port operations is already underway. At Tuas Port, automated yard cranes and horizontal transport move containers between the yard and wharf, with operations managed remotely from a control centre. These systems rely on real-time data and monitoring to coordinate equipment safely in a complex operating environment. To support such operations, PSA is deploying private cellular connectivity, enabling reliable, low-latency communication for automated equipment and future autonomous applications. This shift not only improves productivity but also creates higher-value jobs.²⁹

Concurrently, AI has advanced significantly, with deep integration across sectors for planning, prediction, optimisation, and decision support. The maritime sector is increasingly exploring how AI and data-driven technologies can enhance port and vessel operations. Potential applications include optimising voyages, monitoring machinery performance in real time, and predicting equipment failures before they lead to costly delays.³⁰ As routine reporting and monitoring tasks are increasingly automated, seafarers will be able to focus on critical decisions where human judgement is essential. Over time, the skills required will evolve as seafarers adapt from operating machinery to managing intelligent systems.

Enhanced connectivity, supported by IoT capabilities for ship-to-ship and ship-to-shore communications, enables remote and autonomous operations. Remote operations centres can manage vessels from land using data processed from different sensors to guide autonomous navigation safely. Intelligent systems can also detect hazards and process information from



platforms such as the Automatic Identification System (AIS) to optimise voyages.³¹ These applications enable reduced manning on ships, reshaping how maritime operations are managed and monitored in the future.

In line with decarbonisation efforts, feasibility and efficiency of green technologies can be greatly enhanced by AI and data science. AI-driven optimisation models can analyse data on weather conditions, currents, vessel performance, and port conditions to plan Just-in-Time (JIT) arrivals, adjust speeds and routes, and improve energy efficiency. Within ports, data-driven energy management systems can coordinate the use of equipment, solar generation, and battery storage to smooth demand peaks. As alternative fuels and electrification are introduced, AI and digital twins can simulate bunkering and charging scenarios, plan infrastructure use, and ensure that new fuels are handled safely and efficiently.³² AI and data science enable a “control layer” that turns green technologies from standalone projects into integrated, optimised low-carbon systems across ships, ports, and logistics.

Robotics and AI-enabled systems are increasingly deployed to reduce reliance on divers for hull inspection and cleaning. Remotely operated or autonomous robots attach to a ship’s hull, using cameras and onboard sensors to navigate, inspect surfaces, and remove biofouling. Automating this process enhances safety by minimising diver exposure while shortening inspection and cleaning durations. A smoothly maintained hull reduces drag, leading to lower fuel consumption and associated emissions.³³ Furthermore, robotic solutions enable more frequent and precise maintenance, improving operational efficiency and extending the service life of hull coatings.

These developments in ports and vessels are not isolated innovations, but part of a broader transformation in maritime operations. Smarter ships, equipped with near real-time data updates, enable more reliable scheduling, automated ports alleviate manpower constraints, and digital platforms enhance visibility and control across supply chains. For the industry, this convergence means greater efficiency and resilience. For Singapore, technological advancements reinforce the nation’s role as a trusted and innovative maritime hub, providing forward-looking solutions for the maritime sector.



■ Tuas Port sets the new standard for port automation as the world’s largest automated container terminal when fully completed in the 2040s. (Photo credit: PSA Singapore)

3.5 Ensuring Resilient, Secure, and Safe Maritime Operations in a New Era of Threats

As new technologies are deployed across the maritime sector, safety and security remain the foremost priorities. Singapore manages one of the world's busiest maritime corridors, with thousands of vessels navigating its waters daily in close proximity to the city. In such an environment, even minor lapses in safety and security can result in cascading economic and environmental consequences, including collisions, risks to crew members and port workers, disruptions to port operations, and increased costs for shipping lines.³⁴

Managing these risks while keeping goods flowing efficiently requires advanced vessel traffic services, precise navigation, and seamless coordination among pilots, crews, and port operators.

The transition to alternative fuels introduces a distinct set of safety considerations. Potential low-carbon fuels, such as ammonia, possess unique chemical properties that give rise to new hazards. Toxic vapour leaks or accidental release can pose serious risks to crew health, port personnel, and marine life. Recognising these challenges, MPA is preparing for a multi-fuel future by establishing the necessary infrastructure, regulatory frameworks, and operational safeguards. Safe adoption is crucial not only for achieving decarbonisation goals, but also for maintaining public trust and ensuring worker safety.³⁵



Digitalisation and autonomy are reshaping how safety is managed across shipping and port operations. Increased digital connectivity enables ships and ports to share real-time data, improving scheduling and navigation. However, this connectivity also introduces potential cyber threats, where a security breach could disrupt the entire supply chain. Autonomous ships are progressively taking on tasks such as routing and collision avoidance. While these systems can respond faster than humans, industry trust in them depends on robust cybersecurity measures and clear standards for autonomy.³⁶

Amid these developments, training and simulation tools remain essential. They allow crews and pilots to familiarise themselves with new technologies and prepare for scenarios that are difficult to replicate at sea.

■ *The Advanced Navigation Research Simulator (ANRS) at the Centre of Excellence in Maritime Safety (CEMS) at Singapore Polytechnic is the first navigation research simulator in Southeast Asia. The ANRS consists of a full mission ship bridge and a vessel traffic system which simulates ship navigation and vessel traffic system operations.*



4

Technology & Research Roadmap



4.1 Overview

The Singapore Maritime Technology & Research Roadmap 2026 edition charts the nation's next wave of industry transformation to enhance port efficiency and competitiveness, with safety, security, and sustainability as its foundational pillars. By driving strategic R&D plans, this Roadmap builds industry capabilities and identifies technology opportunities to address broader maritime challenges. These challenges include adapting to shifts in global trade flows, addressing limitations in manpower and space, enhancing port traffic safety, and meeting decarbonisation targets. The Roadmap outlines Singapore's commitment to driving innovation at technology frontiers and strengthening research capabilities. The goal is to ensure that Maritime Singapore remains resilient, competitive, and a future-ready global hub.




The Roadmap outlines four Technology & Research thrusts, namely (i) Autonomous Port Operation, (ii) Safe and Efficient Delivery of Alternative Energy, (iii) Smart Ships, and (iv) Intelligent and Integrated Port Services. Supported by key enablers, these four thrusts aim to achieve an integrated approach towards innovation, operational excellence, and environmental sustainability throughout the maritime value chain. This builds on the Maritime Transformation Programme (MTP) supported under Singapore's Research, Innovation and Enterprise (RIE) plan.

4.2 Autonomous Port Operation

The transition toward autonomous port operation has evolved from a visionary concept into a strategic imperative for global maritime hubs like Singapore. As trade volumes increase and logistical complexities intensify, this shift is driven by the need to overcome the bottlenecks of manual cargo handling. In particular, this thrust embeds intelligence and automation into the core of port operations, moving beyond simple mechanisation to create an integrated ecosystem in which hardware, digital systems, and AI collaborate seamlessly. Critically, it strengthens Singapore's ability to handle increasing cargo volume and throughput, while advancing sustainability through technology.



Thrust 1: Autonomous Port Operation

	Short-term	Mid-term	Long-term
Port Planning and Optimisation 	Modelling and simulation for autonomous port operations		
	Predictive	Comprehensive	Autonomous
	Forecasting of supply chain disruptions		
	Dynamic berth allocation		
	Autonomous horizontal transport fleet		
Port Equipment and Maintenance 	Maintenance		
	Predictive, diagnostics	Prescriptive, prognostics	Self-maintaining
	Automatic inspection and data collection		
Port Operations and Management 	Container cargo process		
		Automated	Autonomous
	Bulk cargo process		
		Semi-automated	Automated
	Automated wharf/berth operations		
Non-intrusive cargo sensing and inspection			



Port Planning and Optimisation

Port planning has evolved from static, schedule-based processes into a dynamic, real-time, and data-driven orchestration. Autonomous port operations will be enabled by an integrated digital ecosystem powered by data, advanced simulation, and real-time analytics. This supports a shift from reactive management to proactive coordination across the port ecosystem. It relies on a synchronised digital environment that integrates real-time feeds from global positioning systems, onboard and port-based sensors, and terminal equipment.

By centralising these data streams, the system will simulate complex operational scenarios. These may range from voyage adjustments caused by shipping disruptions to the precise optimisation of terminal berthing and anchorage. Factors such as vessel priority, cargo type, and services requirements, such as bunkering and repairs, can then be matched with the availability of shore-side assets and landside connectivity. This empowers more informed decision-making. In turn, the integrated approach is envisioned to maximise berth utilisation, minimise vessel turnaround times, and reduce asset idle time.



Port Equipment and Maintenance

The resilience and long-term viability of modern port operations are anchored in the excellence of their critical infrastructure. Through the seamless integration of smart assets, autonomous inspection systems, and continuous data intelligence, port equipment and maintenance can evolve from calendar-based, reactive models to predictive, performance-driven approaches.

Ports can establish this predictive foundation by deploying Artificial Intelligence of Things (AIoT)-powered autonomous systems, such as automated cranes and intelligent horizontal transport vehicles, while shifting from fixed maintenance schedules to data-driven regimes. In the longer term, the vision is to realise autonomous asset resilience. Under this model, equipment would be embedded with self-diagnostic AI capabilities and robotic mechanisms capable of independently executing repairs. This transition would shift the operations from human-reliant upkeep to a resilient, technology-driven model that ensures continuous and high-performance port activity.



Port Operations and Management

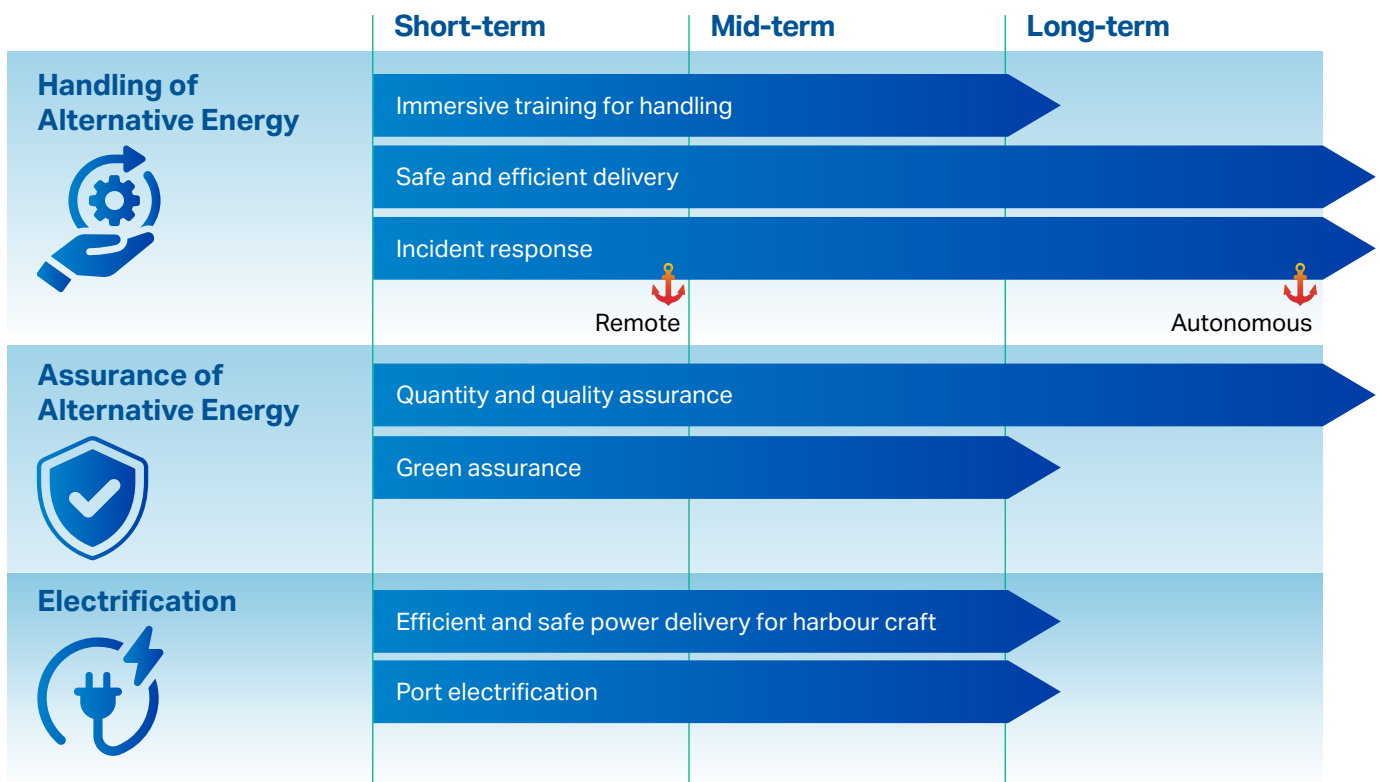
The future of port operations and management lies in the transition from fragmented, siloed processes toward a unified, intelligent, and self-optimising command system. This paradigm shift integrates data, automation, and predictive analytics across both cargo streams and vessel services. It transforms the port into a dynamic and cognitive node within the global supply chain.

Development can include optimising core terminal operations and establishing the digital and automated foundation required for future advancements. Building on this base, efforts can then shift to enhancing workforce safety by automating high-risk and manual tasks, reducing exposure to hazards while improving productivity. These capabilities further strengthen security and safety across the entire port ecosystem, embedding resilience at every operational layer. This phased approach progressively advances towards the long-term vision of fully integrated and autonomous port operations by ensuring a solid foundation for each stage.

4.3 Safe and Efficient Delivery of Alternative Energy

As global shipping moves toward the IMO goal of reducing carbon emissions by at least 70% by 2040, Singapore is paving the way towards a multi-fuel transition. This thrust focuses on ensuring that alternative fuels can be handled and delivered with uncompromising safety and efficiency.

Thrust 2: Safe and Efficient Delivery of Alternative Energy





Handling of Alternative Energy

The handling and delivery of alternative energy presents new safety and operational complexities. Addressing these challenges requires enabling technologies and standards to support higher-efficiency and higher-volume bunkering operations while maintaining stringent safety controls. These include advanced leak detection systems, early prediction of equipment failure, and monitoring of material fatigue. As bunkering operations evolve, robotic and automated solutions can enhance crew safety while improving operational efficiency. This transition is supported by establishing defined safety zones and integrated emergency shutdown systems. It also needs compatibility between port infrastructure and diverse energy types, as well as alignment with international standards to harmonise global bunkering practices. In parallel, strengthening emergency preparedness and response capabilities for alternative energy remains a core priority. Proactive research into fire-fighting medium and advanced detection systems ensures that response readiness keeps pace with the energy transition. This includes the development of specialised tugs, robotic systems, and autonomous drones to safely operate within hazardous zones when required.

To ensure workforce readiness, the use of high-fidelity training technologies can enable operators and emergency responders to practise complex scenarios in a controlled environment. These immersive training platforms bridge the gap between theory and field-execution, ensuring that knowledge and procedural expertise can be effectively applied to real-world operations.



Assurance of Alternative Energy

Assurance provides the governance framework to scale alternative energy reliably, establishing protocols for integrity in monitoring, reporting, and verification. Today, confidence in marine fuels operations is anchored on standards such as SS648 and SS709 digital bunkering systems, and verifiable records. Extending these capabilities will help to align technical and regulatory requirements across fuel types, and ensure consistent and transparent bunkering practices.

A near-term priority is bunker fuel provenance assurance, focusing on technologies and standards to ensure consistent fuel quality from source to the receiving vessel. Beyond this, scientific methods such as isotopic analysis and fuel fingerprinting can strengthen the accounting mechanism and enhance trust in the end-to-end verification of alternative energy sources and sustainability.



Electrification

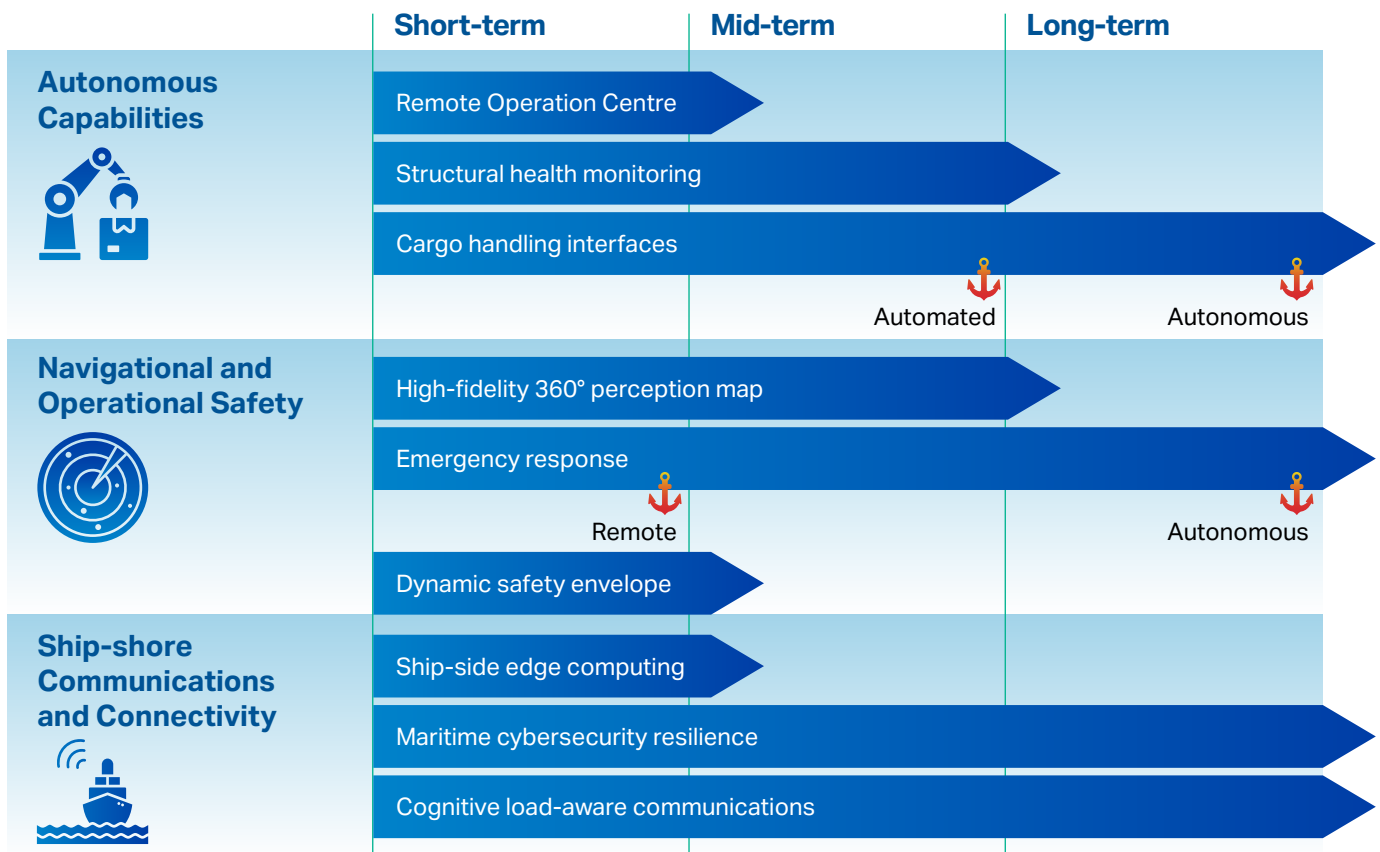
Electrification is driving the transformation of port power systems to cleaner, low-carbon energy sources, to support port decarbonisation. Electrification is also one of the key decarbonisation pathways for domestic harbour craft. Innovative charging solutions within port waters, such as near-shore charging, will optimise space utilisation and free up valuable waterfront sites for other activities.

Efforts also extend to port-side battery technologies, including the repurposing of used batteries in retired automated guided vehicles. Enabling smart and active battery balancing will be essential for extending the operational life of these second-life batteries, creating a sustainable and circular approach to energy storage within port operations.

4.4 Smart Ships

The shift towards smart ships advances operational efficiency and safety within the maritime sector. This thrust focuses on transforming the vessel from a standalone asset into a highly connected, intelligent node within the broader maritime network. By leveraging automation, AI, and data analytics, smart ships improve ship-shore communications, enable the development of MASS, and enhance navigational and operational safety.

Thrust 3: Smart Ships



Autonomous Capabilities

The transition from manned, hybrid, to autonomous operations optimises onboard manning while expanding shore-based capabilities through seamless human-machine collaboration. For example, remote operation centres enable the transfer of roles and responsibilities from sea to shore, underpinned by rigorous frameworks for situational awareness reconstruction and standardised handover protocols.

Concurrently, a shift from manual inspections to automated, real-time health monitoring systems would enable early detection of wear or fatigue. Complementing these developments, automated cargo handling interfaces that leverage robotics and AI to integrate ships with port infrastructure will reduce the need for manual oversight, while boosting operational resilience. The development of these capabilities will be further expanded through broader technological and regulatory developments for maritime autonomy.



Navigational and Operational Safety

Ensuring robust navigational capabilities and safe operations is a prerequisite for smart ship adoption as it addresses the human-factor risks that could lead to maritime incidents. Research into cross-modal data fusion and adaptive geometry algorithms for dynamic safety envelopes around the vessel could augment autonomy with improved perception technologies. As capabilities mature, safety systems can shift from reactive human oversight to machine-led proactive responses such as the development of multi-agent swarm intelligence. Implementation would follow a phased approach, transitioning from remote-controlled intervention to fully autonomous operations that can enhance the overall resilience of the maritime network.



Ship-shore Communications and Connectivity

Ship-shore communications are fundamental to enabling shared awareness and reliable control for remote and autonomous ship operations. Onboard edge computing processes enable localised data processing to overcome connectivity constraints, reducing the systems' satellite dependency while preserving safety-critical information.

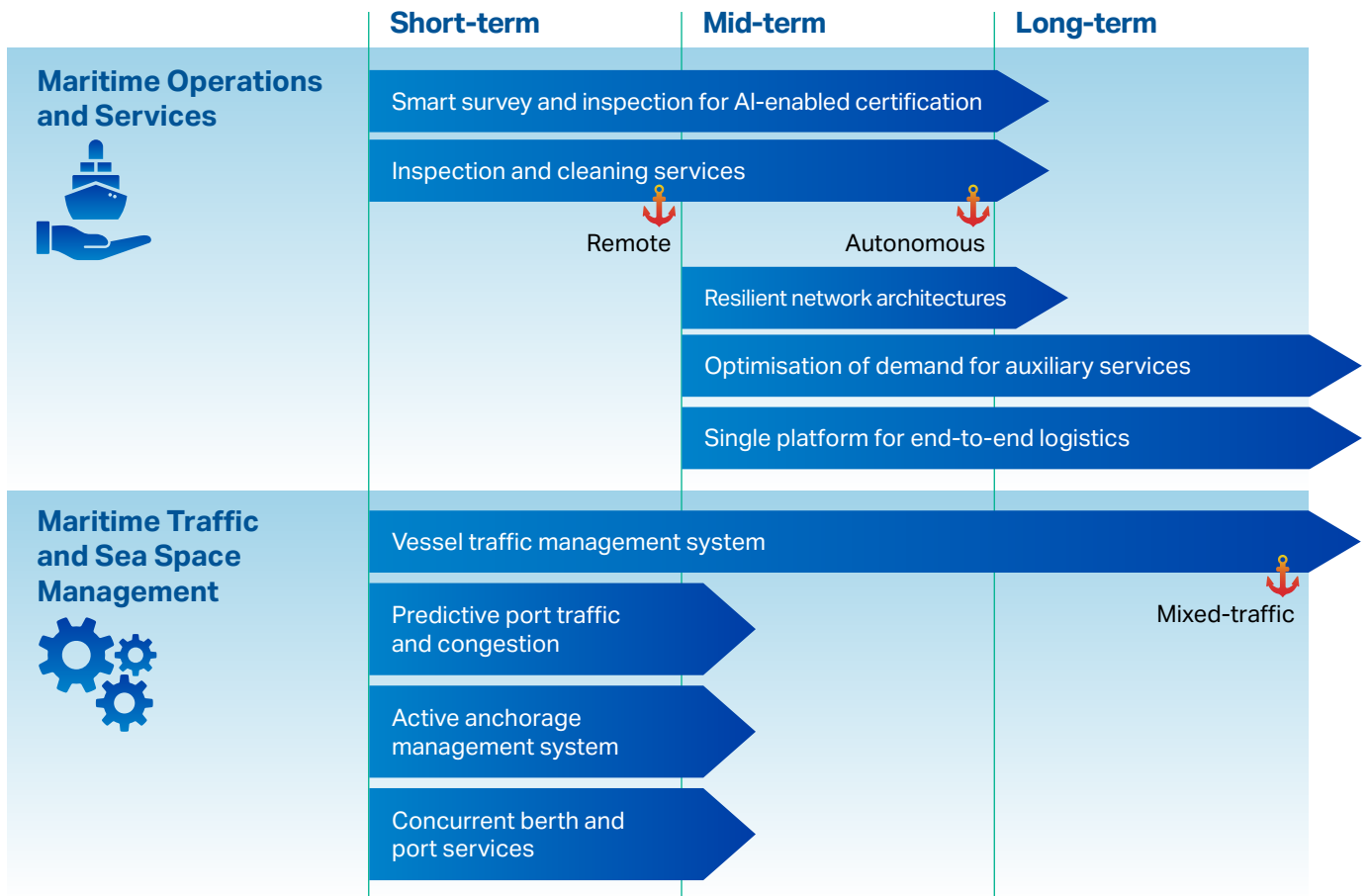
Similarly, cognitive systems can prevent information overload by intelligently prioritising the transfer of critical navigation data over administrative traffic, reducing human errors and ensuring bandwidth for operational needs. For maritime cybersecurity resilience, the focus will be on utilising AI and machine learning to detect anomalies, identify malicious code, and secure control links from interferences.

4.5 Intelligent and Integrated Port Services

The final thrust addresses the backbone of the port – the myriad of supply, services, regulatory clearance, and operational interfaces that require orchestration as part of a vessel's port call. This thrust seeks to deliver a highly efficient and coordinated suite of port, marine, and hydrographic services required as part of a ship's pre-arrival, arrival, and departure. This includes pilotage, towage, bunkering to anchorage, berth operations, husbandry, inspections, surveys, repairs, and maintenance.

To complement and facilitate efficient port call and flow of goods through the Port of Singapore, existing capabilities such as the Maritime Single Window digitalPORT@SG™ and data platform OCEANS-X offer one-stop digital shopfronts to connect MPA with industry, maritime administrations, technology solution providers, and RIs.

Thrust 4: Intelligent and Integrated Port Services



Maritime Operations and Services

Technological advancements are reshaping port operations by reducing workloads and mitigating operational risks. In the area of asset integrity, innovative smart survey and inspection systems could utilise AI-enabled certification and autonomous structural monitoring to transition from episodic checks to continuous, data-driven compliance. In addition, advancing remote-controlled and autonomous robotic solutions for applications, such as underwater inspection and cleaning services, will improve productivity, minimise human safety risks and operational downtime.

The vision of intelligent and integrated port services also requires resilient network architectures and unified digital platforms to enhance port-side and vessel traffic reliability. Research into AI-driven optimisation and prediction to coordinate demand for auxiliary services can also eliminate resource underutilisation and improve turnaround time. Collectively, these efforts will culminate in a single end-to-end logistics platform that integrates fragmented systems into a cohesive digital ecosystem, offering visibility and predictive coordination as a truly “one-stop” service.



Maritime Traffic Management

Robust traffic management is essential for seamless port operations, ensuring vessels navigate safely and efficiently through busy waters. Future research will enhance these systems to forecast congestion ahead of time by ingesting data such as global AIS data, meteorological trends, and climate information. By identifying potential choke points early, these platforms can provide recommendations to mitigate disruptions before they impact port efficiency.

As autonomous vessels become more prevalent, next-generation vessel traffic management systems will need to be future-ready and capable of managing a heterogeneous fleet comprising various operational models. Research on safety frameworks for simultaneous bunkering operations, cargo handling, and supplies will move the industry away from inefficient, sequential workflows. This will create a high-throughput environment that reduces vessel turnaround times and enhances overall port resilience.

4.6 Enablers



Policy and Feasibility Studies

Policy and feasibility studies serve as enablers that align technical research with commercial and regulatory realities. Policy frameworks provide the necessary guardrails and incentives to de-risk high capital investments into new technologies, while feasibility studies validate the operational scalability of new solutions. These foster a conducive environment for multi-stakeholder collaborations, allowing for the establishment of international standards and harmonised regulations that accelerate the transition from research to pilot trials and the development of market-ready applications.



AI and Machine Learning

AI and machine learning leverage huge amounts of maritime data to produce actionable intelligence and automation across domains. Their primary function lies in advanced pattern recognition and reasoning, processing petabytes of images, video, audio, and sensor data.

Beyond detection, AI functions as the central coordinating intelligence for autonomous systems, orchestrating robot swarms, and enabling real-time adaptive sampling. This capability unlocks the value of complementary technologies by converting raw data from fragmented sources into predictive insights and operational intelligence. Evidence-based decision-making across the maritime ecosystem is strengthened as a result.



Maritime IoT and Digital Connectivity

The IoT serves as a central nervous system, transforming vessels and infrastructure into a network of intelligent nodes. At the edge of this IoT architecture, advanced sensors and instrumentation act as integrated data sources rather than standalone tools. These miniaturised nodes can be embedded within various platforms to monitor parameters such as environmental conditions, hull integrity, and fuel quality. These disparate IoT data streams can be synthesised into a coherent digital thread, providing the sensing to action intelligence required for informed, real-time decision-making.

A resilient and secure IoT infrastructure would draw on multi-layered connectivity, including 5G networks and low Earth orbit satellite communications. This would enable real-time exchange of data among vessels, ports, and shore-based operations. It would also support AI applications, digital twins, and autonomous operating models. This robust connectivity ensures that the port remains operational amid disruptions while enabling services such as remote vessel control and advanced harbour craft operations.



Additive Manufacturing

Advanced manufacturing techniques are increasingly being deployed to translate digital designs into certified, operational maritime components. In particular, additive manufacturing enables the production of complex and performance-optimised parts, including lightweight structures and components with enhanced material properties suited for marine environments. Beyond prototyping, current efforts are focused on scaling the technology for industrial use through improved process reliability, material qualification, and component certification.

In the maritime sector, additive manufacturing is being explored to address long-standing supply chain challenges by enabling on-demand production of spare parts closer to the point of use, including distributed manufacturing. This reduces lead times, minimises vessel downtime, and lowers reliance on extended global supply chains. Parallel efforts across industry and research are working to establish standards, quality assurance frameworks, and digital inventories to support the broader adoption of additively manufactured parts for operational vessels. As these technical and regulatory barriers are addressed, additive manufacturing is expected to play a growing role in maritime supply chain resilience. It will support maintenance operations and enable the production of specialised components across the sector.



Robotics

Robotics automates high-risk and labour-intensive tasks across port and ship operations. By integrating autonomous mobile robots and specialised robotic arms, the industry can transition towards more consistent, precise, and safer execution of maintenance, cargo handling, and inspection activities. These systems reduce human exposure to hazardous environments while ensuring that operational standards remain high and predictable.

Beyond physical automation, robotics enables new operating models such as remote hull cleaning and automated underwater inspections. When coupled with real-time data feeds, robotic platforms provide the physical capability to act upon digital intelligence, allowing for faster response times and improved asset longevity. For a global hub like Singapore, the development of these robotic solutions is essential to maintaining a resilient maritime gateway that can scale its capacity and safety standards through technological sophistication.

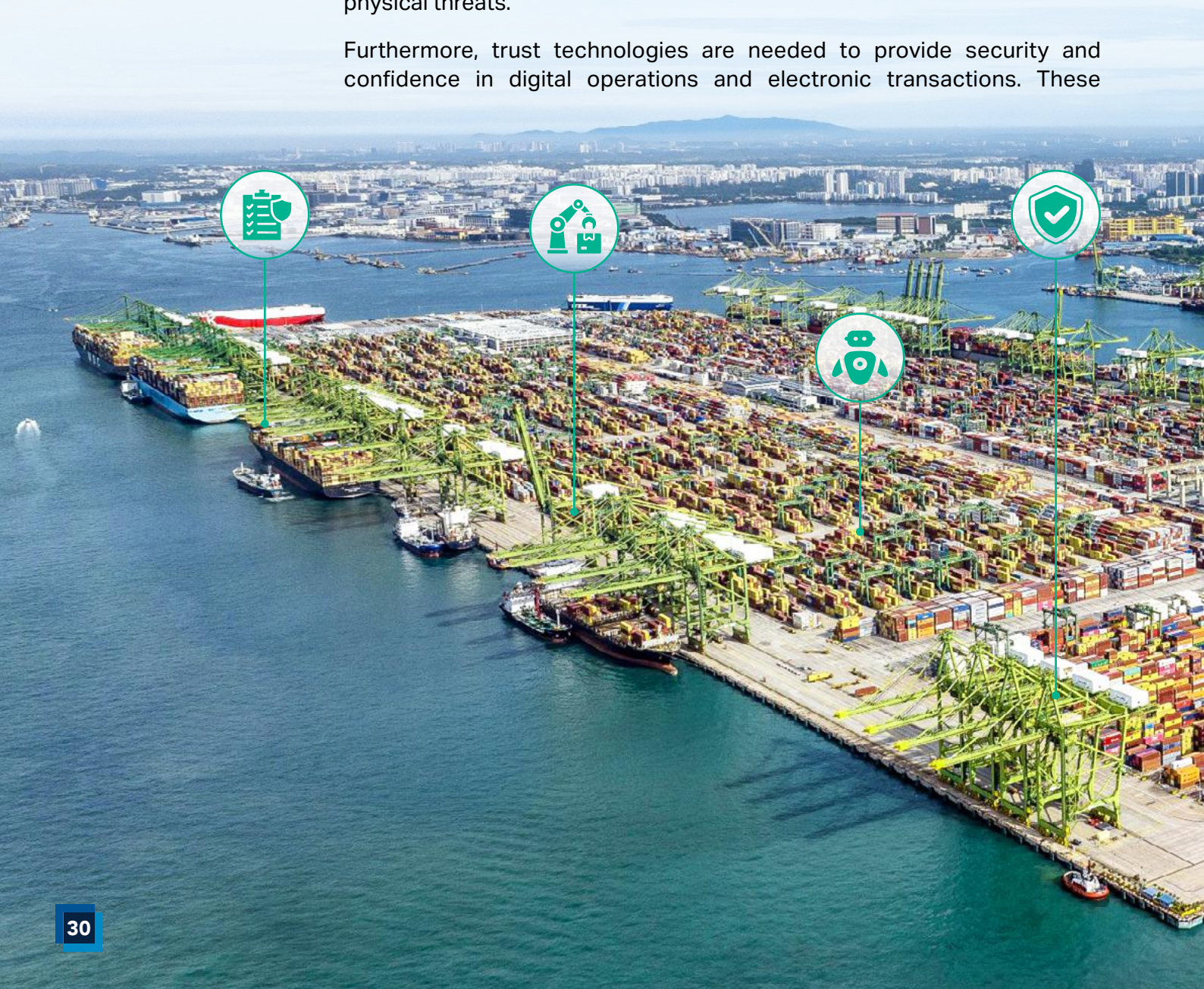
The next frontier lies in embodied AI, which equips robotic systems with situational awareness, adaptive decision-making, and the ability to operate safely alongside human workers in dynamic, unstructured port environments.



Cybersecurity and Trust Technologies

As maritime operations become increasingly digitalised and autonomous, cybersecurity evolves from a traditional information technology function into a core operational and safety imperative. This enabler includes intrusion detection systems tailored to maritime protocols, secure and resilient communication architectures, and safeguards against cyber-physical threats.

Furthermore, trust technologies are needed to provide security and confidence in digital operations and electronic transactions. These



frameworks ensure that data remains tamper-proof, fostering the necessary confidence for multi-stakeholder collaboration and information sharing. In a highly connected digital economy, they provide the assurance needed to keep the maritime ecosystem reliable and resilient against evolving digital threats.



Quantum Technologies

Quantum technologies present significant opportunities for the maritime industry in sensing, secure communications, and computational capabilities. In the near term, quantum sensing offers potential for ultra-high-resolution seabed mapping and drift-free inertial navigation in global positioning system denied environments by detecting minute gravitational and magnetic variations. Simultaneously, quantum communications and quantum key distribution offer tamper-detectable links to secure critical maritime infrastructure, autonomous vessel networks, and ship-to-shore data transmission.

In the longer term, quantum computing is expected to solve complex optimisation challenges such as large-scale fleet routing and supply chain resilience modelling. Collaborations with Singapore's research ecosystem remain essential in the exploration of innovative applications of quantum technologies and positioning the sector for future breakthroughs as development in quantum hardware matures.



5

From Vision to Action



5.1 Executing the Maritime Innovation Agenda

The maritime sector stands at an inflection point. Shifts in global supply chains, environmental mandates, and technological advancements are rapidly reshaping the industry. In this landscape, failing to act would undermine the long-term competitiveness of any maritime hub.

Singapore recognises this imperative. Through MPA and SMI, we have built a strong foundation. We have established core research capabilities, nurtured a pipeline of research talent, and fostered academia-industry partnerships to turn real-world challenges into tangible solutions. These collective efforts have created a vibrant innovation ecosystem in Singapore.

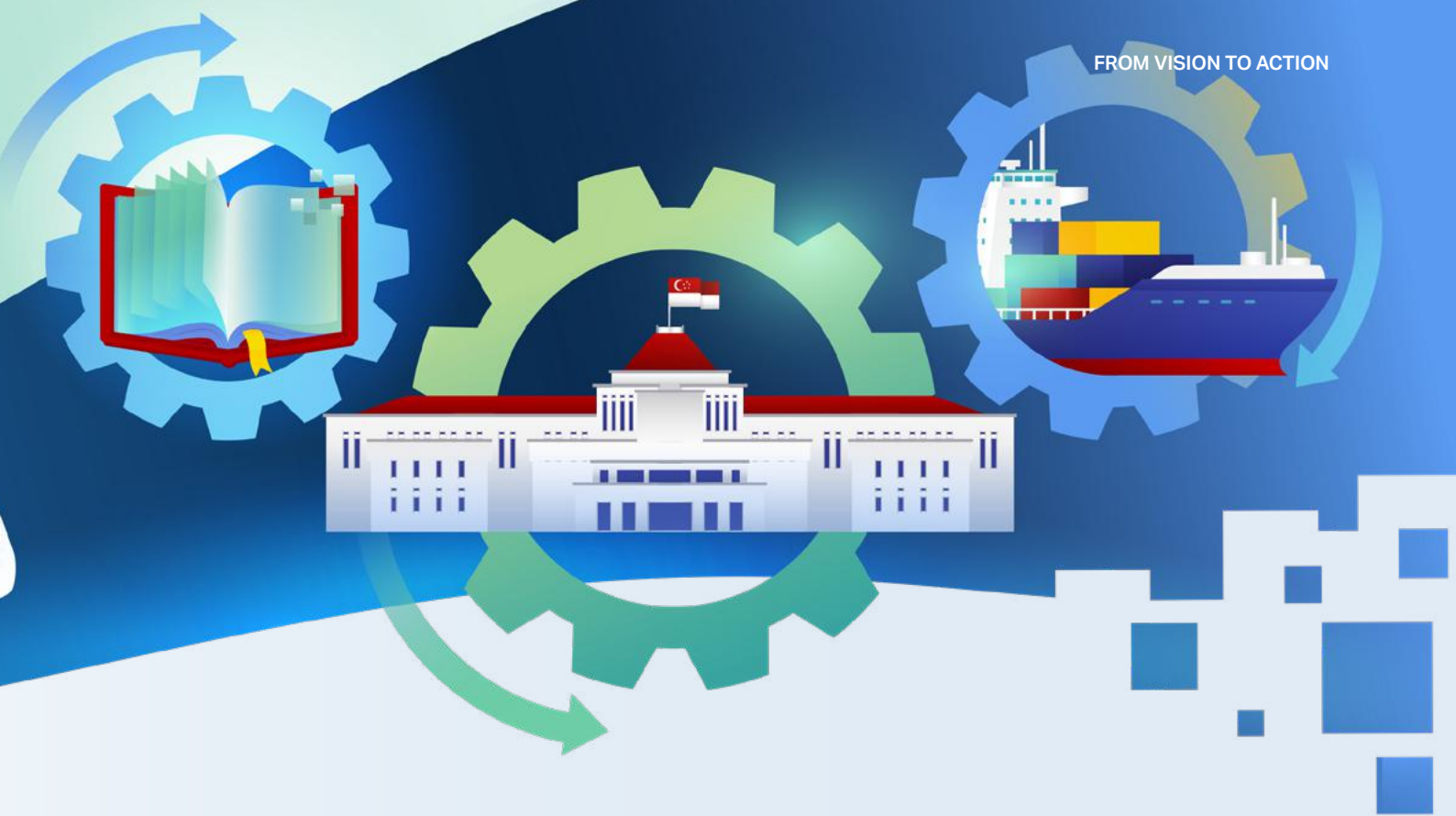
This chapter highlights the capabilities that are being developed and details the support needed to help them succeed, from funding mechanisms to collaborative platforms. It provides clear direction for our RIE community and industry partners, guiding our collective efforts to build capabilities that the maritime industry needs.

Success, however, depends not on vision alone. Industry, RIs, and government must forge deeper partnerships, align investments with strategic priorities, and accelerate the translation of innovation into operational reality.

 A photograph of the interior of the Singapore Maritime Gallery. The room is bright and modern, with large windows overlooking a cityscape. On the left, a large wall display features the text "The Future Is Now." in a bold, sans-serif font. In the foreground, a curved white display structure is visible, with the words "Maritime Traveller" printed on it. The floor is light-colored, and the ceiling has exposed ductwork and lighting fixtures.

The Future Is **Now.**

■ The Singapore Maritime Gallery presents Singapore's maritime heritage and its position as a leading global hub port shaped by innovation and technology.



5.2 Core Research Capabilities of Ecosystem

Thrust 1: Autonomous Port Operation



Robotics and Automation of Container Handling

Robotics and automation deliver the critical physical intelligence machines need to sense, adapt, and act with precision in a terminal's complex and dynamic environment. This expertise spans from hardware design and intelligent control algorithms to sensors and full-scale system integration.

A core capability is developing specialised robotic hardware to automate high-risk, manual tasks, such as twist lock handling. Traditionally, workers manually secure containers with heavy twist locks, a physically demanding and repetitive task with a high risk of injury. Automating this process with purpose-built robotic arms improves efficiency, keeps workers out of harm's way while enabling them to take on higher-value supervisory roles.

Adding advanced sensing technologies to terminal assets gives machines spatial awareness in the complex port environment. For example, equipping quay cranes with Light Detection and Ranging (LiDAR)-based Simultaneous Localisation and Mapping (SLAM) allows the cranes to perceive their surroundings with precision, enabling reliable and autonomous container positioning. With real-time vision feedback, robotic systems can dynamically adapt to stay accurate even when lighting changes or loads shift.

These interconnected initiatives build Singapore's expertise in port robotics, creating an ecosystem where hardware and intelligent controls work together to make terminal operations safer and more efficient.



Port Modelling and Simulation

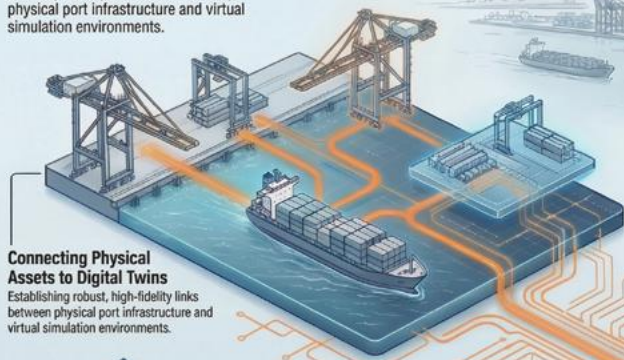
For autonomous port operation to function safely and efficiently, all equipment – cranes, land-based assets, and vessels – must work as one coordinated system. This requires predictive intelligence through modelling and simulation, which acts as the “brain” that enables autonomous systems to anticipate, adapt, and optimise in real time.

A key capability lies in large-scale discrete-event simulation, which models the complex spatial, temporal, and operational dynamics of container terminals, supply chain hubs, and multimodal transport networks. These models are enhanced with multi-objective optimisation and AI-driven decision-making for autonomous yard operations, dynamic berth allocation, intelligent resource coordination, and proactive disruption management. Together, these enhancements provide real-time decision support and scenario analysis for autonomous systems. Crucially, these simulations are constantly checked against live port data to keep the “brain” in sync with what is happening on the ground.

A key parallel effort is the systems engineering and workflow integration that connects this “brain” to the physical assets. This includes developing communication middleware, safety protocols, and human-machine interfaces so that optimised schedules can be carried out reliably and safely.

THE DIGITAL TWIN ARCHITECTURE

Creating the digital twins and linking physical port infrastructure and virtual simulation environments.



Connecting Physical Assets to Digital Twins

Establishing robust, high-fidelity links between physical port infrastructure and virtual simulation environments.

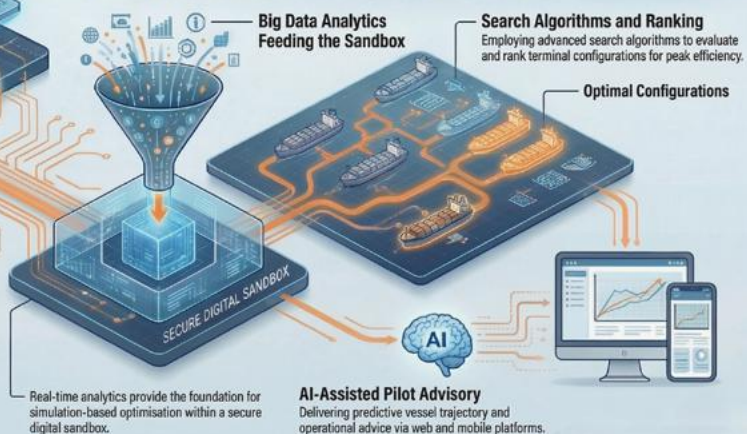


Modular “Lego-Brick” Formalism
Utilising IKEA-mode code encapsulation for flexible, plug-and-play extensions of port components.



High-Fidelity Emulation
Mimicking real-world operating environments to improve the accuracy of test results for target engines.

SIMULATION-BASED OPTIMISATION WORKFLOW



Big Data Analytics Feeding the Sandbox

Search Algorithms and Ranking
Employing advanced search algorithms to evaluate and rank terminal configurations for peak efficiency.

Optimal Configurations

Real-time analytics provide the foundation for simulation-based optimisation within a secure digital sandbox.

AI-Assisted Pilot Advisory
Delivering predictive vessel trajectory and operational advice via web and mobile platforms.

The Centre of Excellence in Modelling and Simulation for Next Generation Ports (C4NGP) at National University of Singapore leverages discrete-event simulation modelling and digital twin platforms to deliver operational optimisation, scenario analysis, and real-time decision support for modern port and logistics systems.



■ MESD and Ammonia Safety & Training Institute conducted the Ammonia Release Field Experiment at the Military Operations on Urban Terrain site in Fort Ord, California, USA, in October 2024.

Thrust 2: Safe and Efficient Delivery of Alternative Energy



Alternative Energy Trials and Validation

An important capability pillar in Singapore's maritime decarbonisation strategy is the conduct of pilot trials and validation of alternative energy pathways. The work includes alternative energy pathway modelling, trials, emissions monitoring, life-cycle assessment, and safety and risk analysis. Together, these efforts provide the real-world data needed to safely and effectively adopt alternative maritime energy. They also enable the maritime industry to manage the transition without making long-term investments that risk becoming stranded assets.



Mitigation Technologies

Enabling a secure shift toward alternative bunkering requires specialised capabilities to pre-empt, identify, and neutralise potential fuel-related hazards. A key advancement is the high-fidelity simulation of accidental fuel dispersion during bunkering. By integrating physics-based models, data-driven surrogates, and real-time environmental data, these simulations aim to accurately predict the behaviour of hazardous plumes in both air and sea. These predictive capabilities are embedded into the Maritime Digital Twin platform, enabling real-time plume visualisation, toxicity and flammability risk assessment, and faster emergency response.

Other developments include proprietary shelter-in-place strategies and mitigation measures for loss-of-containment scenarios. Studies have also explored drone deployed water curtains to mitigate ammonia plume dispersion. Collectively, these capabilities enhance public safety, inform evidence-based regulatory policies, and support safer bunkering operations as the industry scales up alternative energy adoption.



Integrated Smart Energy and Intelligent Marine Systems for Harbour Craft Electrification

A core capability is combining sustainable ship and system design with efficient charging infrastructure and onshore microgrids for the electrification of harbour craft. A system-of-systems framework enables global optimisation of vessel design, operational strategies, and charging systems, providing a clear, cost-effective approach for the electrification of Singapore's harbour craft fleet.

Supporting this effort are new technologies in marinised energy management systems, high-efficiency chargers, and an energy storage sizing tool that leverages digital twins and route-speed-battery simulations to optimise the performance of electric harbour craft.

■ Researchers from Singapore Institute of Technology's Future Ship and System Design Programme examined the propeller shaft compartment aboard *Pyxis R*, Singapore's first solar-powered electric vessel. The research programme charts a course toward a net-zero maritime industry through sustainable ship and smart system design.





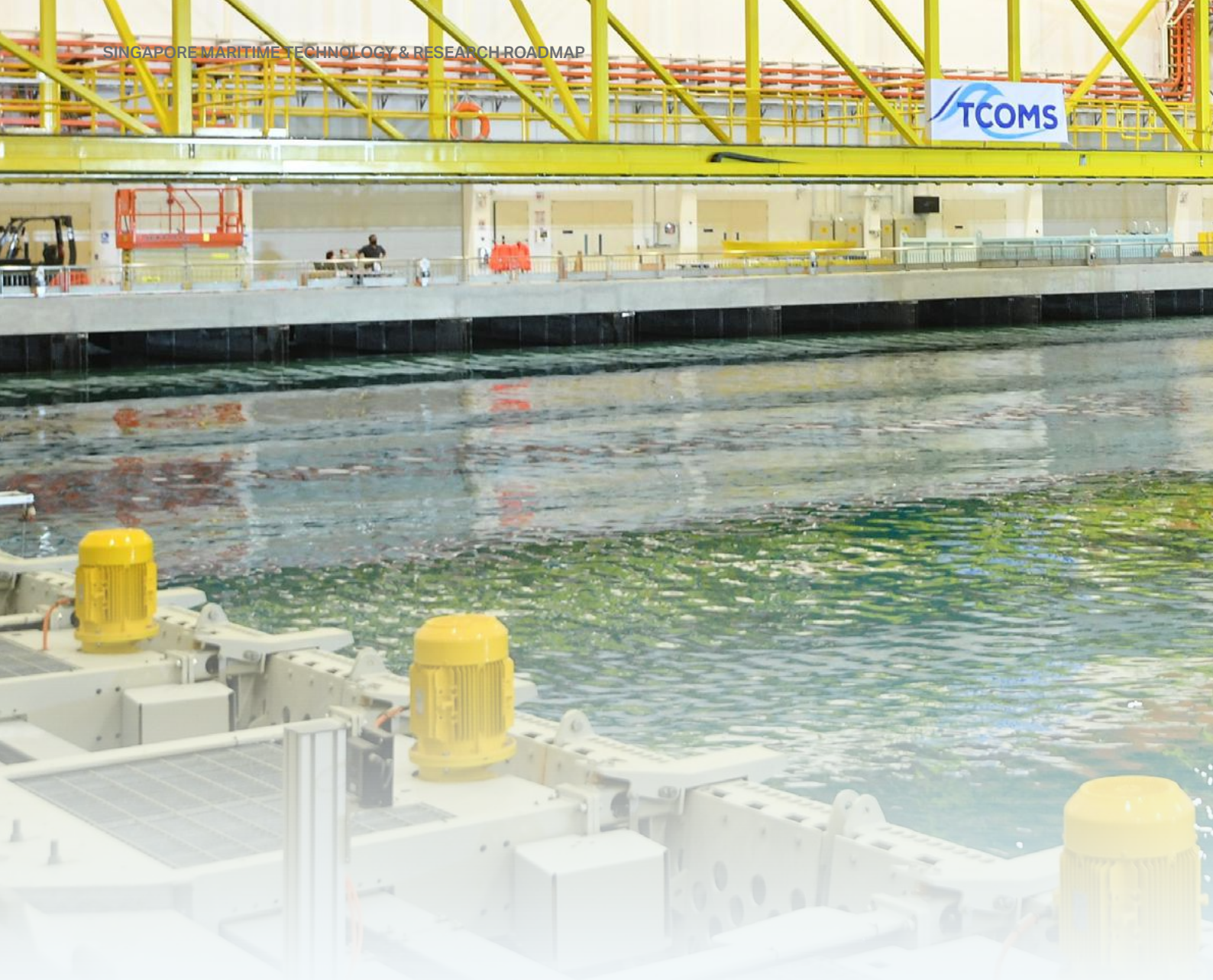
■ CEMS brought its immersive methanol safety training technology to the IMO, spotlighting how next-generation training tools are preparing seafarers for the shift toward alternative fuels.



Full-cycle Decarbonisation Assessment for Integrated Decision Support

A core capability is the integrated decision support that applies rigorous Life-cycle Assessment (LCA), combined with techno-economic and risk analysis, to de-risk the adoption of new energy solutions for ocean-going vessels. Rather than analysing the impact of fuels in isolation, the framework assesses environmental, economic, and safety consequences across a vessel's entire lifecycle. This ensures that GHG mitigation strategies do not inadvertently introduce other ecological or social risks.

This integrated methodology provides a holistic view of trade-offs. Well-to-Wake assessments map emissions and resource consumption from primary fuel production to end-use, giving a clear account of environmental impacts. The analysis extends beyond fuel pricing to calculate Total Cost of Ownership, including infrastructure retrofits, maintenance, and crew training. This is complemented by an integrated safety and risk analysis that identifies hazards associated with new fuels, such as toxicity and explosivity, and model mitigation strategies before major investment decisions are made.



Thrust 3: Smart Ships



Safe and Secure MASS Operations Through Integrated Intelligence

Singapore is developing an integrated data-driven intelligence capability to enhance the safety and performance of MASS. This framework combines vessel AIS data with advanced models of ship motion, added resistance, fuel consumption, and power requirements into a comprehensive performance database. It is augmented by a quantified risk index and spatial-temporal risk-mapping system that leverages real-time metocean data to assess collision-avoidance risks dynamically. This helps to ensure that all decisions follow the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) for safe autonomous and remotely operated navigation.

This core capability also serves as the engine for generating realistic, high-fidelity test scenarios to rigorously validate autonomous systems. By reconstructing real-world encounters from AIS and metocean data, baseline scenarios can be established and then stress-tested through hazards such as sudden weather changes or unexpected vessel manoeuvres. Additionally, these performance models allow operational



■ The next-generation Deepwater Ocean Basin research facility at the Technology Centre for Offshore and Marine, Singapore (TCOMS) is equipped with advanced wave and current generation systems to simulate challenging ocean environments that marine platforms and ships operate in. The Centre of Excellence for Autonomous & Remotely Operated Vessels (CEAOPS) at TCOMS will tap on such facilities to develop autonomous related technologies.

constraints to be simulated, so that decision-making can be tested under conditions of high added resistance or limited power. This approach moves testing beyond abstract scenarios and grounds it in real operating conditions, helping to ensure that MASS are prepared for the dynamic and complex realities of the sea.



Metocean Modelling

Metocean modelling provides the foundational data infrastructure needed for smart ships and autonomous maritime operations. This capability delivers real-time, high-resolution environmental intelligence (waves, tides, currents and wind) to support predictive analytics and data-driven decision-making. A core component is a spectral wave model for the Singapore Strait, driven by European Centre for Medium-Range Weather Forecasts data and validated against satellite and tidal-gauge measurements. This high-resolution forecasting system establishes a reliable, operationally validated metocean foundation for Singapore's maritime community, enabling operators to better predict environmental impacts on vessel performance.



Predictive Maintenance of Vessel

Predictive maintenance transforms vessel operations by enabling a shift from reactive or time-based approaches to condition-based, data-driven strategies. By continuously analysing sensor data, operational parameters, and environmental conditions, this capability identifies early indicators of degradation, forecasts remaining useful life, and determines optimal intervention timing. For smart and autonomous vessels, this reduces unplanned downtime, improves vessel availability, and enhances operational safety, while minimising the need for onboard human intervention.

Central to this capability is an integrated structural health monitoring and maintenance management system that combines computational fluid dynamics and finite element modelling with real-time sensor data assimilation. While initial deployments have validated the predictive maintenance model – demonstrating measurable gains in operational efficiency and reduced inspection cycles – scaling this success requires further research. Broader adoption will depend on adapting intelligence models to accommodate a wider range of vessel types, diverse operational profiles, and various failure modes.

- Supported by the SMI and developed in collaboration with iTrust at the Singapore University of Technology and Design, the Maritime Testbed of Shipboard Operational Technology (MariOT) system is the world's first industrial-grade cyber-physical platform designed to strengthen shipboard cybersecurity training and testing for technologies.





Shipboard Cybersecurity

Singapore has established the world's first industrial-grade cyber-physical testbed for shipboard operational technology. This platform enables rigorous stress-testing of systems against real-world cyber threats, facilitating the development of multi-layered defences and strengthening resilience against emerging vulnerabilities. Building on this foundation, shipboard cybersecurity capabilities can be extended to address the unique requirements of MASS. This will ensure reliable and secure connectivity through robust data architecture protocols and cybersecurity measures for the communication infrastructure linking autonomous vessels with shore-based operations control centres.



AI-driven Human-centric Safety Systems

The core capability is an integrated platform that blends rule-based logic with continuous, data-driven risk assessment. It brings together human dynamic physiological indicators – such as heart rate – with vessel operations, equipment conditions, environmental elements, and human-centric safety considerations. Combined with predictive analytics, this platform protects seafarer well-being in digitalised maritime operations by detecting high-risk states, including fatigue and heat stress, in real time. It automatically triggers alerts, tests mitigation measures, and delivers dynamic safety indices through a live monitoring dashboard, enabling data-driven accident prevention and continuous industry-wide improvement.



Thrust 4: Intelligent and Integrated Port Services

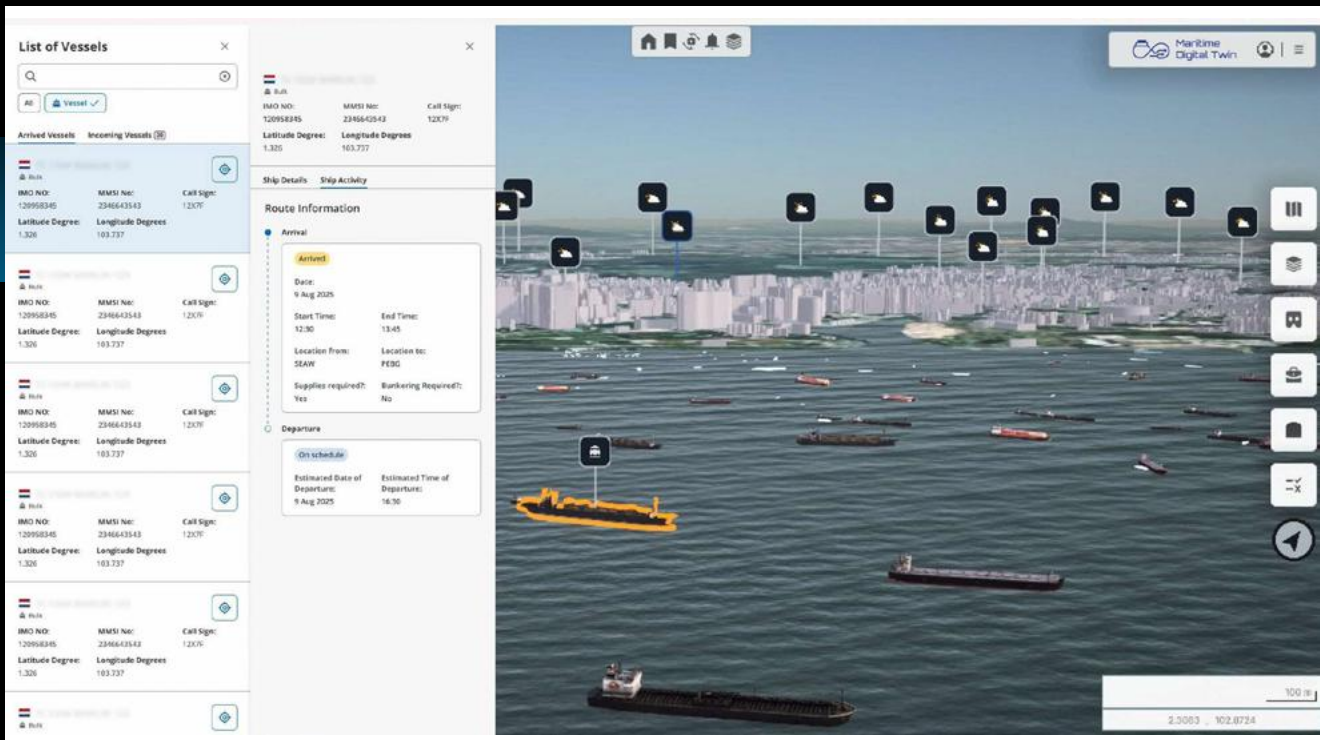


Data-driven Maritime Traffic Intelligence

As vessel calls become denser and time sensitive, ports increasingly rely on data-driven insights to manage traffic safely, minimise congestion, and cut emissions from waiting and manoeuvring ships. A key capability is big-data-driven maritime intelligence, including AI-based traffic and congestion modelling. Digital intelligence enables smoother and greener approaches into Singapore through AI and machine learning models that predict pilotage-area arrival times. This supports JIT arrivals that reduce fuel consumption and improve the predictability of port calls. These core models and datasets also support national initiatives such as digitalPORT@SG™ and JIT planning frameworks, while large-scale AIS and environmental data are leveraged to simulate traffic patterns and congestion, enabling more coordinated marine services across every port call.



Developed by A*STAR for the Maritime AI Research Programme, AI4JIT is an AI-based system for JIT operations that enhances planning and improves overall operational efficiency. (Image credit: A*STAR)



Bridging Digital and Reality: Singapore's first Maritime Digital Twin (MDT) is a dynamic real-time virtual representation of the Port of Singapore. Powered by AI, the MDT enables optimisation of port efficiency, operational decision-making, and strengthening of safety and security, fostered through cross-ecosystem collaboration.

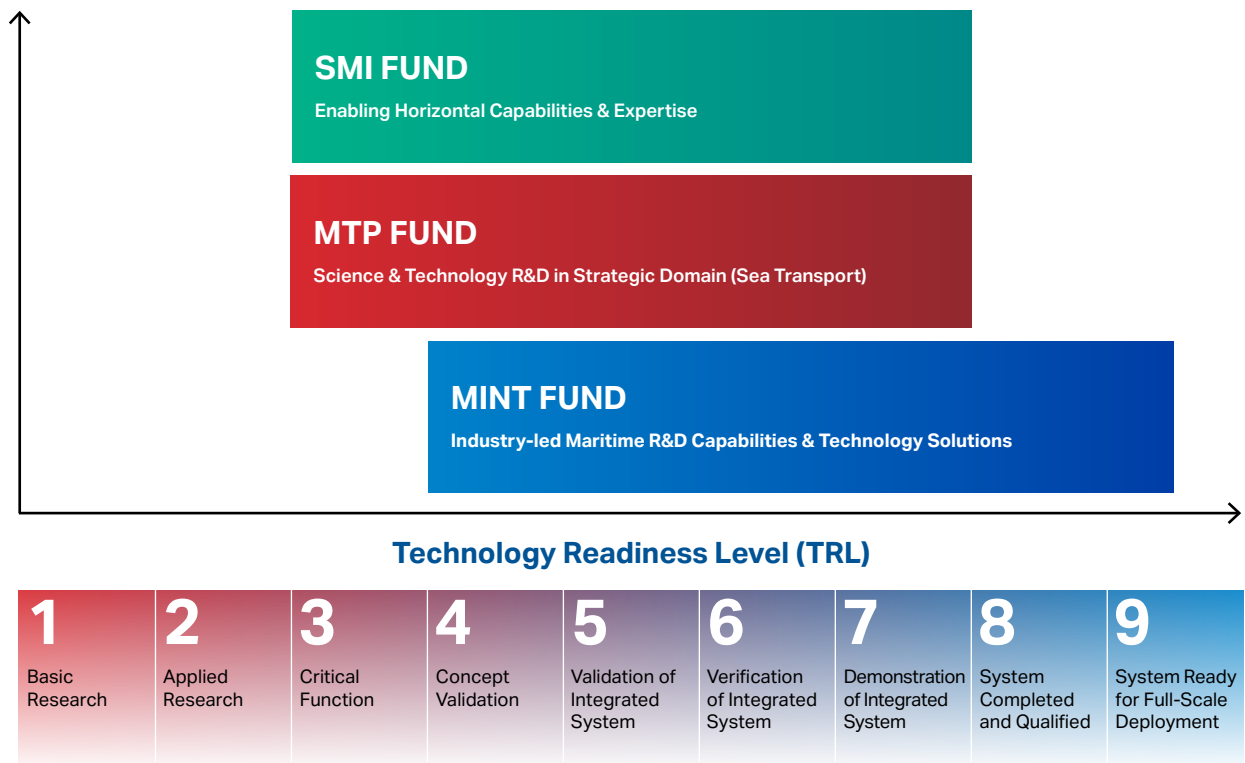


Predictive Operations and Vessel Risk Profiling

Predictive vessel risk profiling empowers maritime operations and services by providing early, data-driven intelligence into vessel safety and operational vulnerabilities. Leveraging AI, this capability facilitates proactive service delivery and foster a more predictable, resilient maritime ecosystem. Researchers are developing AI-based vessel risk profile estimation and classification models that use Large Language Models (LLMs) to extract key incident details and contributing factors from textual reports. These insights are combined with multi-source data such as AIS records, historical incidents, port boundaries, sailing distance, port calls, vessel age, and flag state to generate comprehensive risk features. An enhanced feature selection pipeline and multiple machine learning models then predict each vessel's likelihood of an incident within the next year, while an LLM-based explanation module translates model outputs into vessel-specific recommendations for proactive risk management, targeted safety interventions, and data-driven decision. When integrated with complementary AI models for near-collision detection and explainable traffic safety risk analytics, this framework enables end-to-end monitoring of high-risk vessel behaviours, from historical incident patterns to real-time manoeuvring and traffic interactions.

5.3 Ecosystem Orchestration

MPA and SMI work closely to orchestrate R&D and innovation in the industry. MPA sets strategic directions aligned with national maritime and research priorities, while SMI catalyses collaborations across industry, academia, and RIs to translate R&D into operational outcomes. SMI also informs policy development by contributing evidence-based analyses and technical expertise that support the formulation of national initiatives and regulatory frameworks. Together, we ensure that all innovations are relevant, scalable, and impactful for Singapore’s maritime ecosystem.



Key Maritime Funding Initiatives to Power Innovation

The SMI Fund focuses on building horizontal capabilities and expertise to establish Singapore as a global maritime knowledge and innovation hub. Its primary purpose is to develop industry-ready R&D talent and thought leaders in Institutes of Higher Learning and RIs. Additionally, it expands knowledge frontiers in technoeconomic and policy studies, promotes Centres of Excellence as the go-to nodes for R&D, and supports the translation of projects to higher Technology Readiness Levels.

The MTP Fund supports the industry’s transition towards a more productive, innovative, and sustainable future by co-funding projects that drive technology adoption, capability development, and workforce transformation. With MPA as the implementing agency and SMI as the programme office, the MTP Fund plays a key role in enabling public-private partnerships by facilitating industry’s access to deep technical expertise and cutting-edge research capabilities. The fund focuses on R&D efforts that support early-stage innovation, prior to projects advancing to pilot phases and solution deployment. In doing so, it helps to strengthen digitalisation, decarbonisation, and operational resilience across port, shipping, and maritime services.

The Maritime Innovation and Technology (MINT) Fund advances Singapore's maritime technology landscape, providing essential support for innovation and transforming the sector into a productive, technology-driven cluster. It mainly operates through two schemes: (1) Maritime Innovation and Technology–Research & Product Development (MINT-RPD), which supports maritime-relevant product development and test bedding, including intellectual property and capability development; and (2) Maritime Innovation and Technology–Startup Grant (MINT-STARTUP), which helps the industry co-innovate with technology start-ups through proof of concept or pilot projects for start-ups that have completed the PIER71™ or other approved maritime accelerator programmes.



PIER71™: Growing Maritime Start-up Ecosystem

PIER71™ (Port Innovation Ecosystem Reimagined @ BLOCK71) plays a central role in nurturing Singapore's maritime start-up ecosystem by providing a structured pathway for start-ups to engage industry partners and develop solutions for real-world port and shipping challenges.

The Smart Port Challenge is a flagship initiative under PIER71™ aimed at driving innovation across the smart port and maritime sectors. Organised by MPA and NUS Enterprise, the Challenge encourages the development of technology-driven solutions to address real-world port challenges. By fostering collaboration between industry partners and start-ups, it accelerates the development and adoption of practical solutions to support future-ready smart ports and maritime operations.

■ *The Smart Port Challenge, organised annually by PIER71™, brings together technology start-ups and maritime industry partners to develop innovative solutions that address real-world challenges in Singapore's port and shipping sectors.*





Driving Talent Development and Creating New Jobs Through Maritime R&D

SMI adopts a comprehensive talent development strategy to translate R&D investment into tangible economic outcomes for Singapore. By funding targeted research and nurturing specialised human capital, the initiative aims to generate high-value job opportunities within the local maritime ecosystem. This approach ensures that R&D advances not only yield technological breakthroughs but also help to create new industry-aligned roles, research teams, and innovation functions within Singapore-based enterprises.

Central to this strategy is the SMI – MaritimeONE Postgraduate R&D Scholarship programme, which develops a strong local pipeline of researchers with deep domain expertise. By supporting advanced training in maritime-related disciplines, the programme builds industry-relevant R&D capabilities and prepares Singaporeans for specialised careers in emerging fields such as smart shipping, decarbonisation, and maritime digitalisation.

Complementing this is the SMI Fellows Scheme, which focuses on the development and retention of senior research leaders in strategic maritime R&D areas. The scheme recognises Fellows for advancing high-impact research, mentoring the next generation, and contributing expert knowledge beyond their home institutions. By facilitating deeper engagement with MPA and industry partners, the scheme strengthens cross-sector collaboration and helps to anchor R&D-intensive investments in Singapore. This, in turn, fosters the growth of new research teams and creates quality jobs for Singaporeans, reinforcing the nation's position as a global maritime knowledge hub.





Global Collaboration, Local Impact: Singapore's International Partnerships in Maritime R&D

SMI advances its international collaboration strategy by partnering with leading global RIs, classification societies, and maritime technology companies to drive joint research and accelerate innovation. These collaborations span universities such as the Massachusetts Institute of Technology and the Norwegian University of Science and Technology, enabling the co-development of solutions aligned with international standards and industry needs.

In parallel, SMI convenes global stakeholders through flagship platforms such as Singapore Maritime Research Conference, which brings together academia, industry, and policymakers from around the world to exchange insights on emerging maritime R&D trends. The conference serves as a catalyst for new partnerships, talent development, and long-term research agenda-setting, featuring global leading institutions.

■ *The Singapore Maritime Research Conference and SMI Research Showcase at Singapore Maritime Week 2025 provided a platform to share research advances with the global maritime community.*



6

Conclusion



Dr CHEN XINWEI
Deputy Executive Director
Singapore Maritime Institute

The next decade of maritime will not be shaped by those who simply adapt to change, but by those who dare to define it. The Singapore Maritime Technology and Research Roadmap 2026 edition is our bold declaration: Singapore will be among the definers.

This Roadmap is a collective endeavour. I extend my sincere appreciation to the industry leaders, researchers, and public agency partners who contributed their insights and expertise through workshops and consultative engagements. Your contributions have been essential in shaping a strategy that is both ambitious and actionable. This is not SMI's plan alone, it is our shared roadmap for maritime advancement.

Building on the MTP, this Roadmap is designed to deliver transformative outcomes through systemic integration. Envision a connected future where smart vessels, integrated with port digital twins, operate seamlessly at electrified terminals – voyage optimised for sustainability, operational excellence, and supply-chain resilience. This is the future we are building.

To realise this vision, SMI is evolving from a research funder into a strategic partner and enabler of co-innovation. Our mission is to de-risk pioneering concepts, convene world-class expertise, and transform Singapore's maritime ecosystem into a living testbed. We invite industry players, RIs, and entrepreneurs to bring us your hardest challenges, and to partner on pilots, standards, and commercialisation pathways.

We will also cultivate a new generation of maritime innovators with systems thinking and multidisciplinary mastery. Through specialised fellowships, industry-academia programmes, and venture-focused initiatives, we aim to establish Singapore as the global crucible for maritime talent and venture creation.

We will measure success by tangible value creation: technologies commercialised, standards influenced, and new markets opened from Singapore. This Roadmap is the instrument for that advancement.

The blueprint is ready. The opportunity is now. SMI stands prepared to advance our collective ambition with clarity, partnership, and disciplined execution. Join us with your ideas, your teams, and your commitments. Let us sail forward together to chart the new frontiers of maritime possibility.



About the Maritime and Port Authority of Singapore



MPA was established in 1996 with the mission to develop Singapore as a global hub port and international maritime centre, and to advance and safeguard Singapore's strategic maritime interests. MPA takes on multiple roles as Singapore's maritime and port regulator and planner, international maritime centre champion, national maritime representative, and champion of maritime digitalisation and decarbonisation efforts. MPA partners industry, research community and other agencies to enhance safety, security and environmental protection, facilitate maritime and port operations and growth, expand multi-domain capabilities, and support the cluster of maritime services and manpower development.

For more information, please visit www.mpa.gov.sg

About the Singapore Maritime Institute



SMI is a joint effort by the MPA, the Agency for Science, Technology and Research (A*STAR) and the Singapore Economic Development Board.

Established in April 2011, SMI develops strategies and programmes to achieve its mission with key focus areas in sectors such as port, shipping and maritime services. SMI charts the maritime research strategy and promotes greater industry-academia R&D collaborations to be undertaken in Singapore.

Through a whole-of-government approach, SMI drives initiatives with industry-wide impacts to enhance the overall competitiveness of the local maritime industry, and to strengthen R&D capabilities in support of Singapore as a global maritime knowledge hub.

For more information, please visit www.maritimeinstitute.sg

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The workshop followed a structured, collaborative pathway from strategic positioning to development of a tangible plan. It aligned participants on vision and context, prioritised key challenges, and developed targeted initiatives with clear outcomes. The session concluded with a cross-functional “marketplace” to refine ideas and build a unified, time-phased roadmap. Building on this momentum, a consultative approach was subsequently undertaken with selected industry partners to validate the findings, gather deeper operational insights, and ensure that the proposed initiatives remain grounded in real-world needs.

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- Nanyang Technological University (NTU)
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- Singapore Institute of Technology (SIT)
- Singapore Polytechnic (SP)
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- National Additive Manufacturing Innovation Cluster (NAMIC)
- National Robotics Programme (NRP)
- Office for Space Technology & Industry, Singapore (OSTIn)



Industry

- ABB Group
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- American Bureau of Shipping
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